Searching for GRB Counterparts to GW Events from the Third Gravitational Wave Observing Run with Fermi-GBM and Swift-BAT

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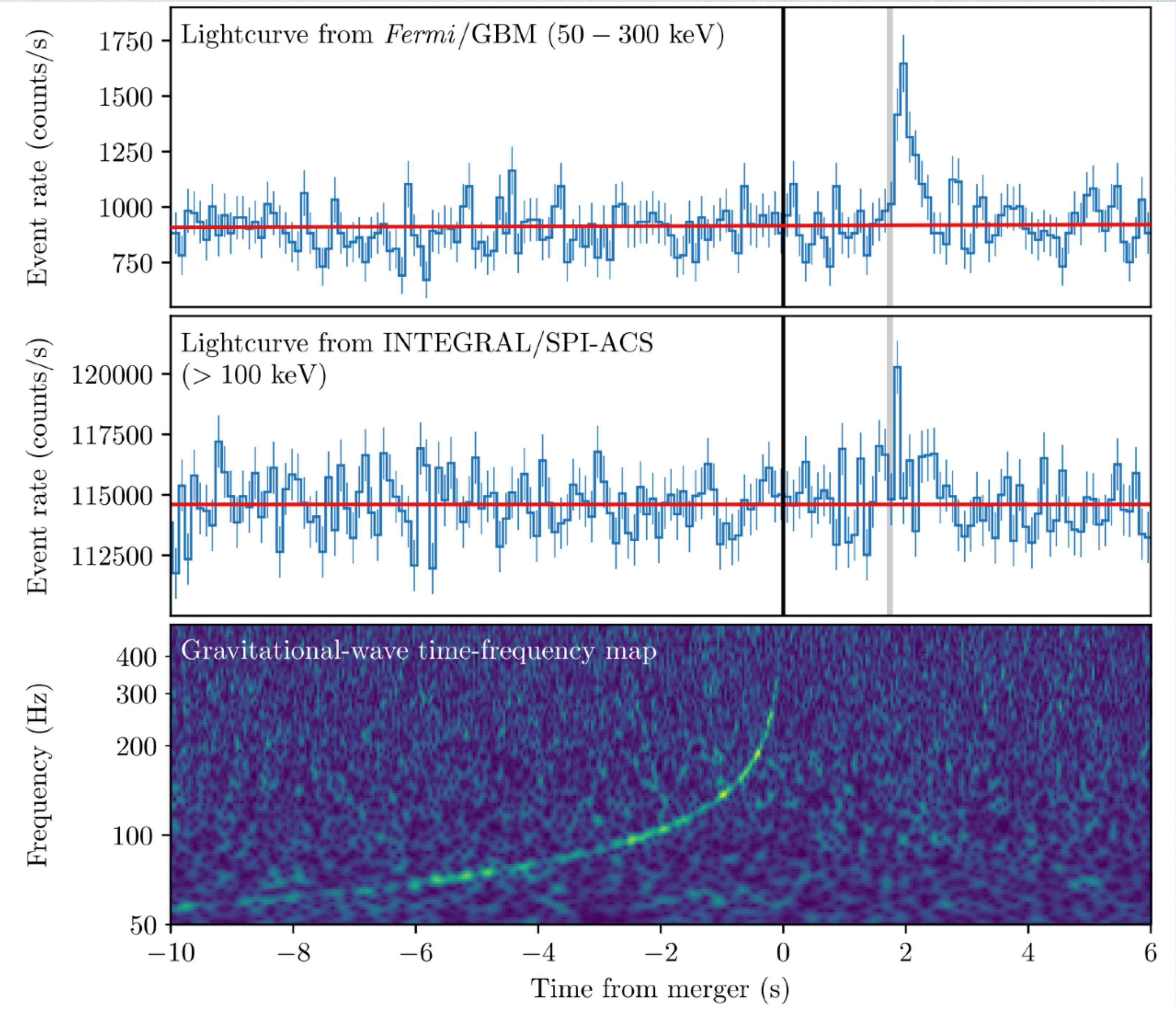
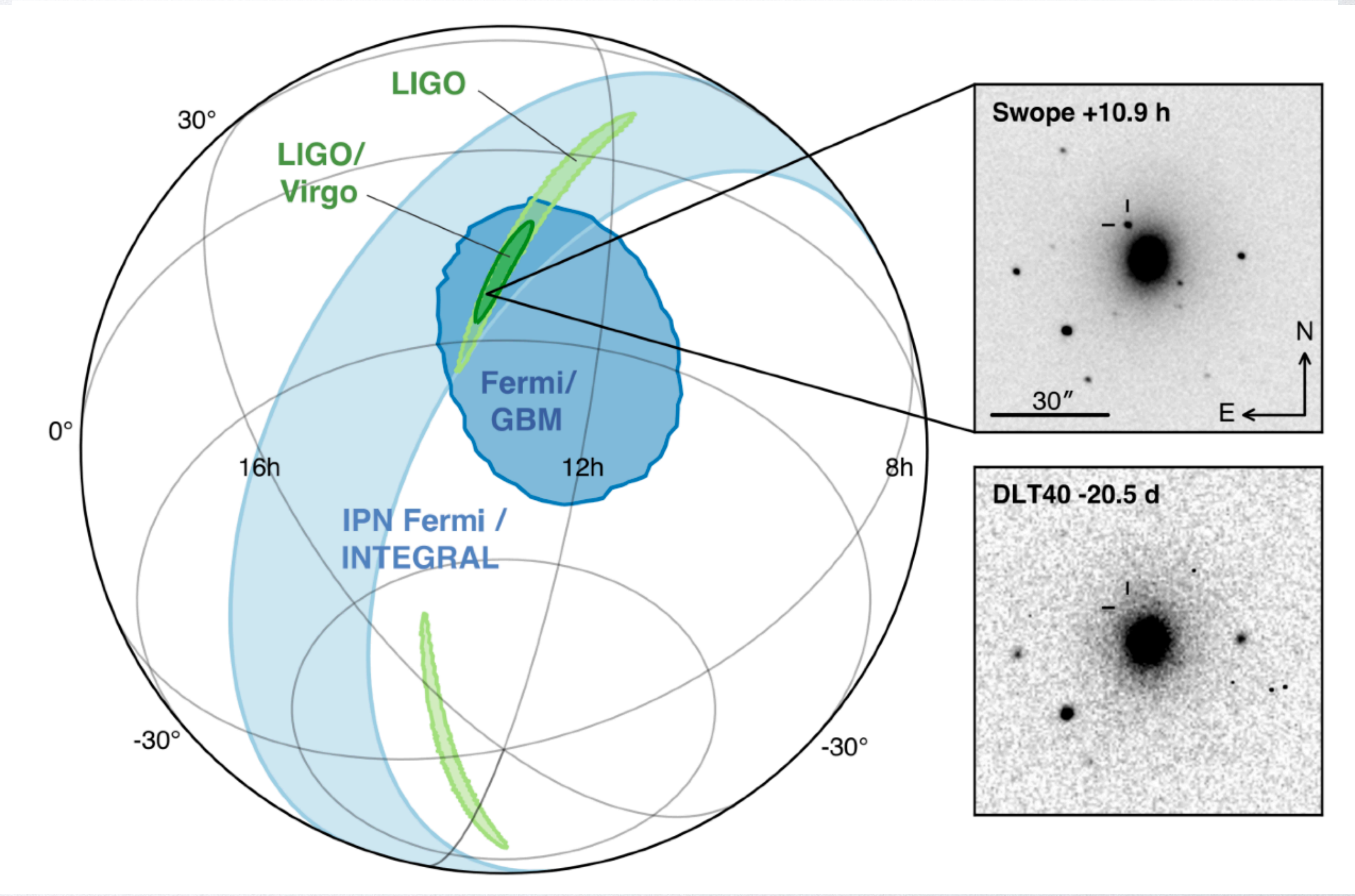
241st AAS 2023

Motivation

B. P. Abbott *et al* 2017 *ApJL* **848** L13

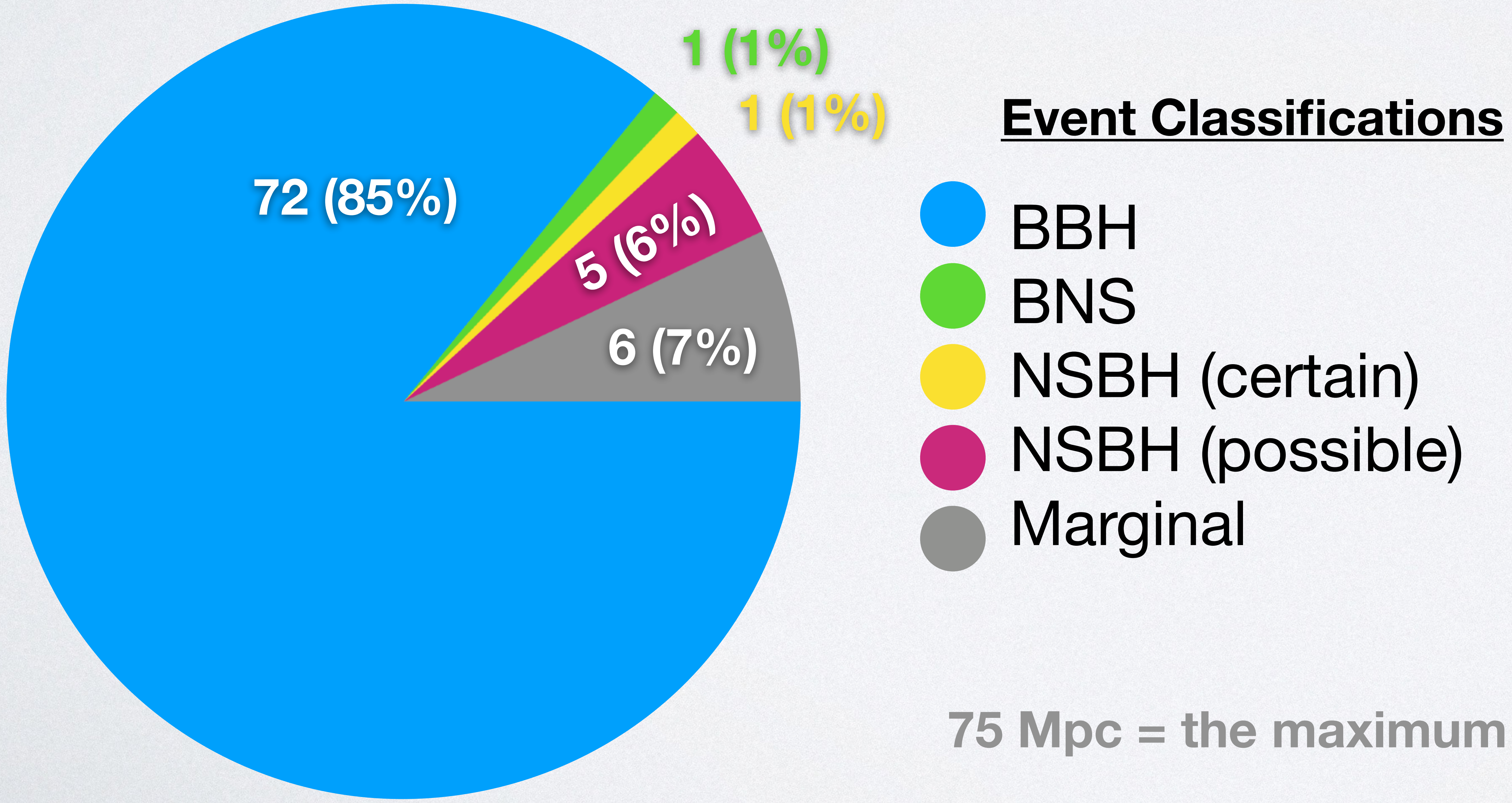
- **The joint detection of GRB 170817A / GW170817** provided incredible insight into a number of topics:
  - binary neutron star (BNS) mergers are progenitors to short GRBs
  - constraints on gamma-ray emitting region in the GRB
  - constraints on speed of gravity, Lorentz invariance, Shapiro delay
  - origins of heavy elements via subsequent kilonova
- **But plenty of questions remain to be answered**
  - rate of short GRB / kilanova production via BNS merger
  - structure of off-axis emission in GRBs
  - expected time delay between GW and GRB, which in turn informs measurements of fundamental physics parameters like speed of gravity
- **We need more joint detections of BNS events!**

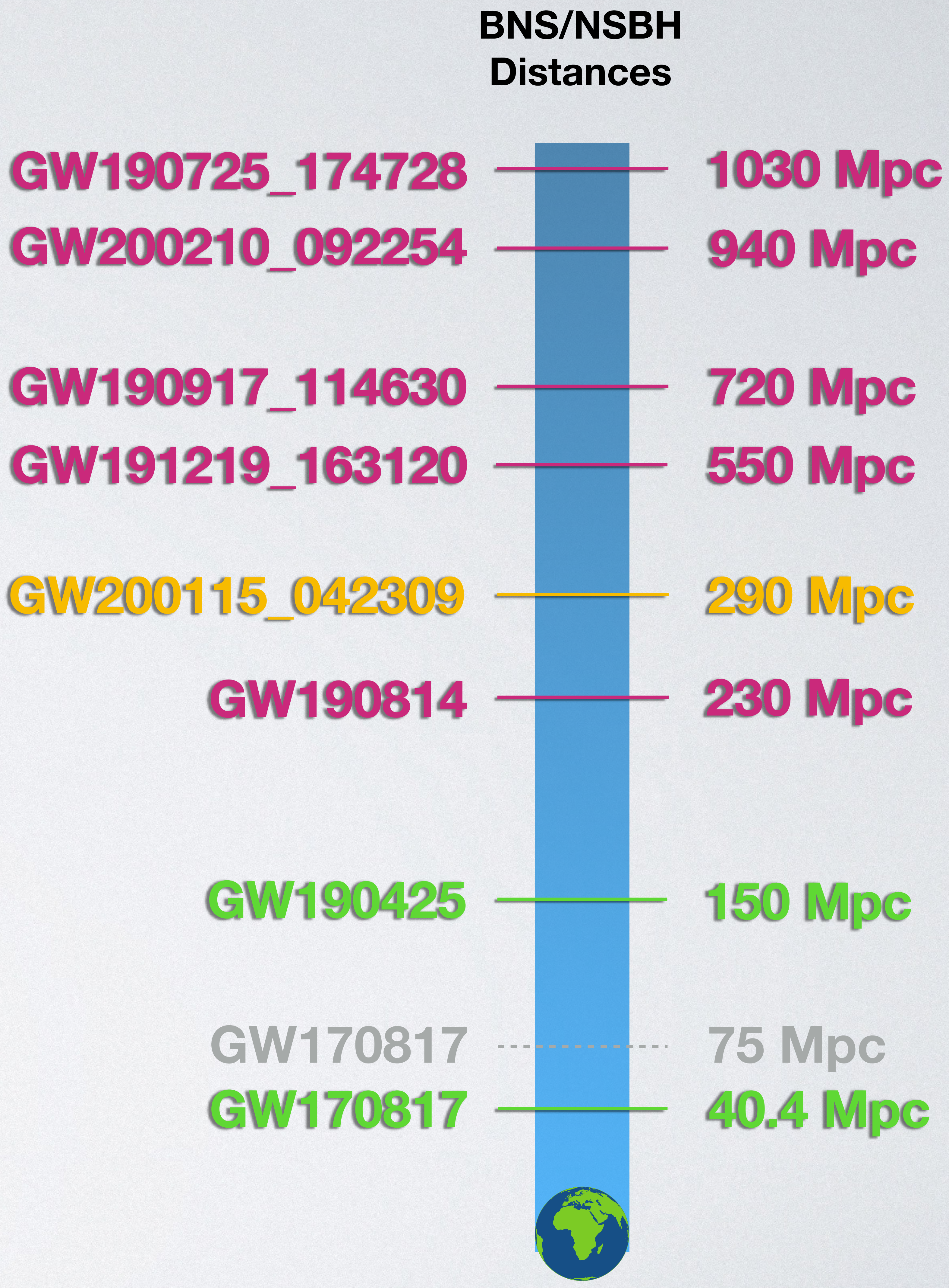




Third Gravitational Wave Observing Run (O3)

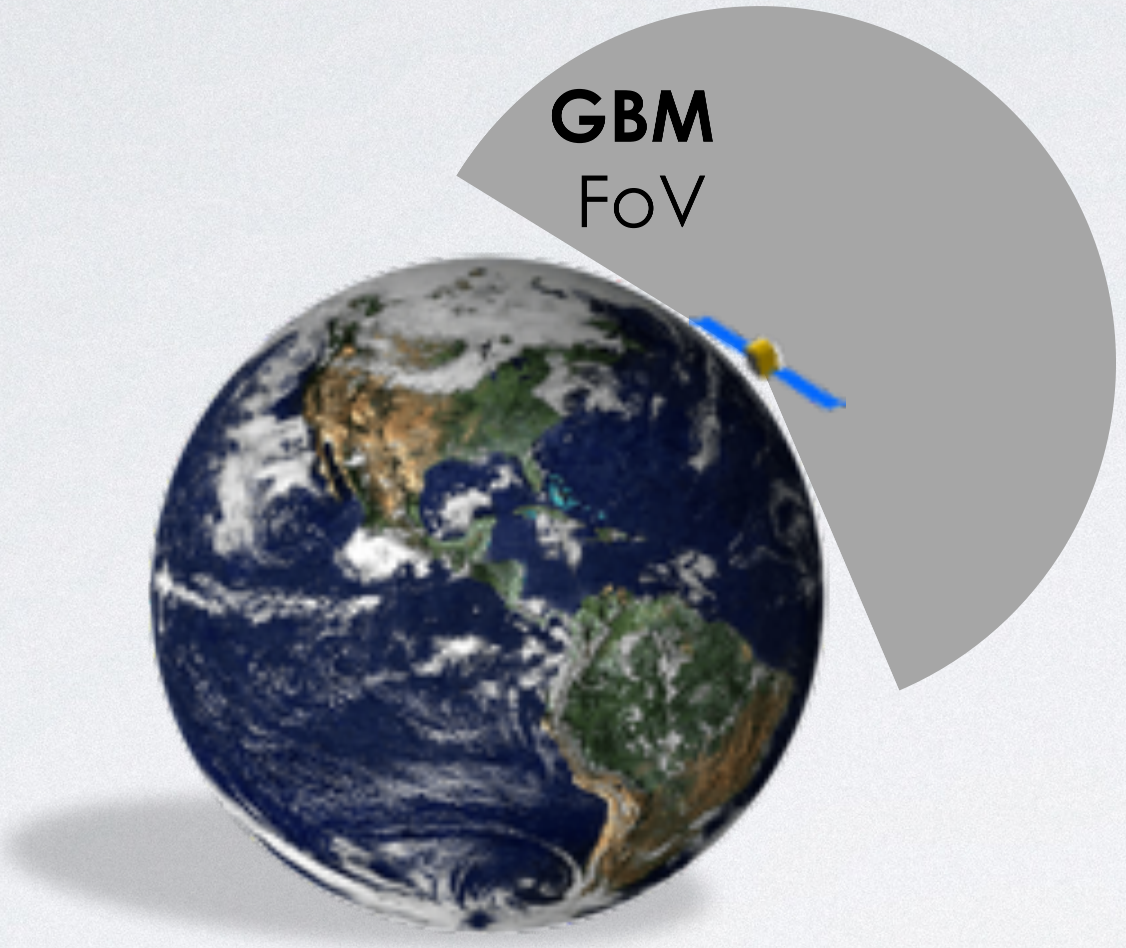
- Following sensitivity upgrades, LVK conducted its **third observing run from April 2019 to March 2020**
- Subsequent catalog publications GWTC-2, 2.1, and 3 containing a **8-fold increase in GW events** that are likely to be astrophysical (79 new events with $p_{astro} > 0.5$), 6 marginal events with FAR < 2 per year, $p_{astro} < 0.5$

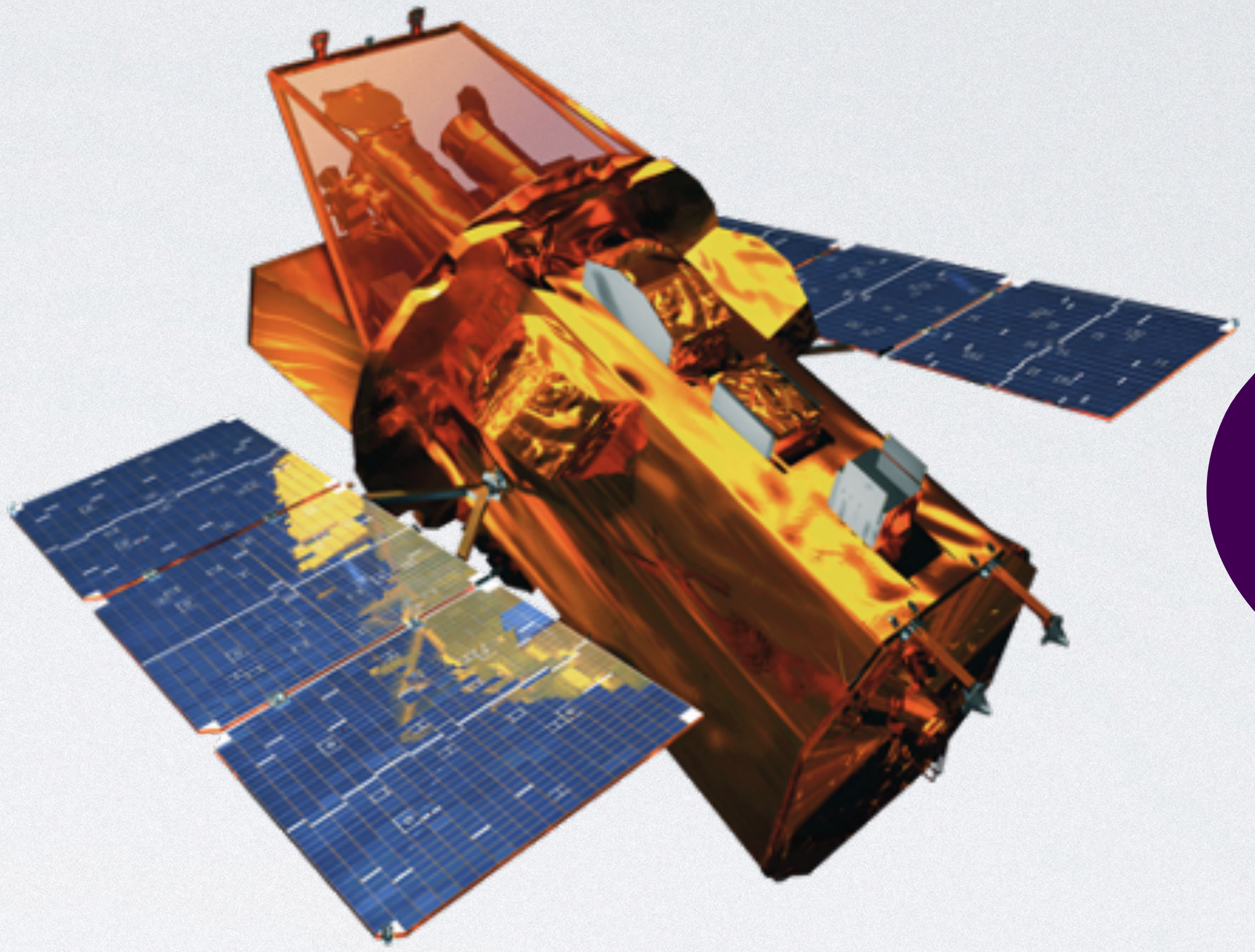


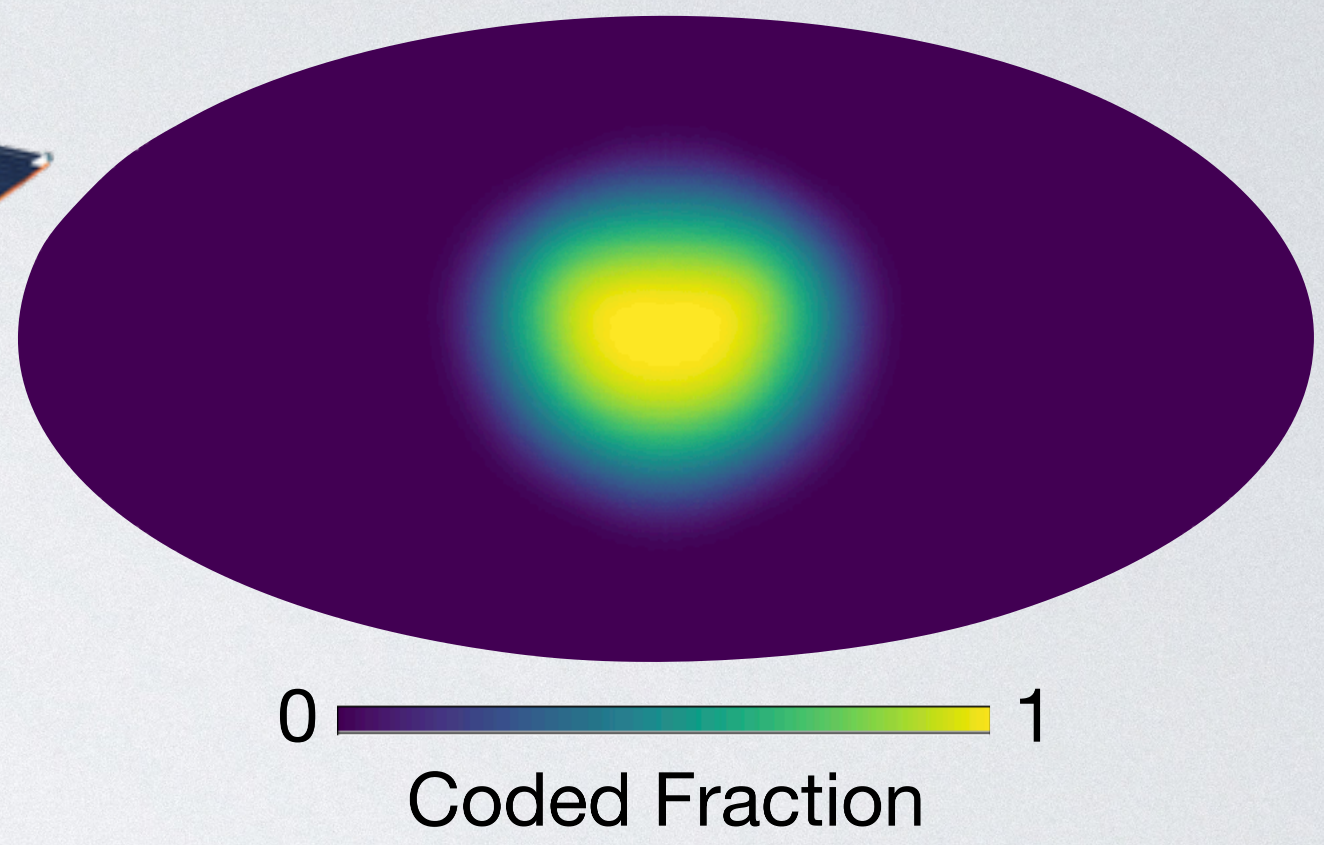


75 Mpc = the maximum distance where Fermi-GBM could detect GW170817

Complementary Instruments







Gamma-ray **B**urst **M**onitor (GBM)

- >8 sr field-of-view (FoV)
- Covers entire sky every ~90 min
- Localizations ~few deg
- Energy range: 8 keV - 40 MeV

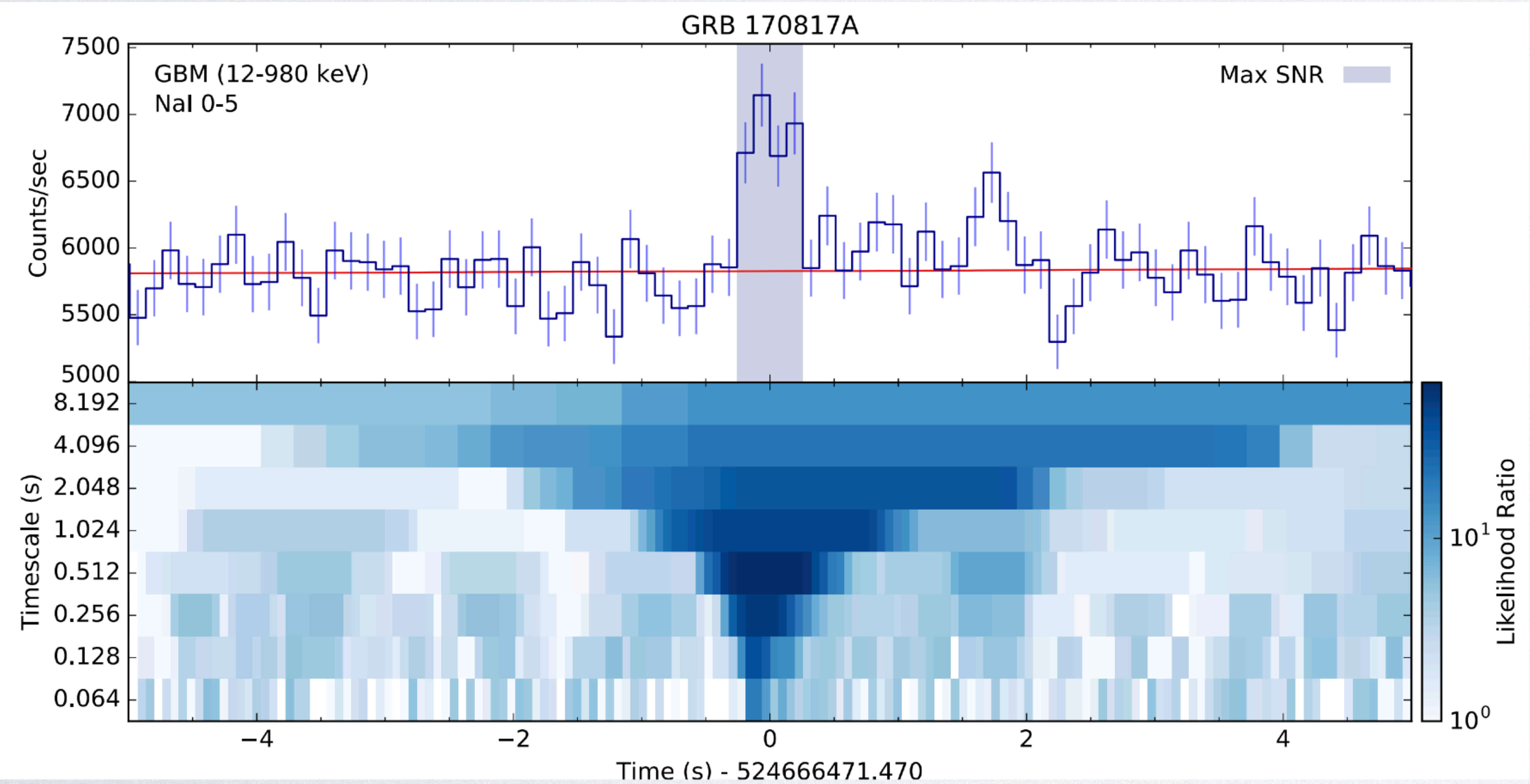
Burst **Al**ert **T**elescope (**BAT**)

- 2.2 sr FoV
- Sensitive to lower fluxes than GBM
- Localizations ~few arcmin
- Energy range: 15 keV - 350 keV (rate data)

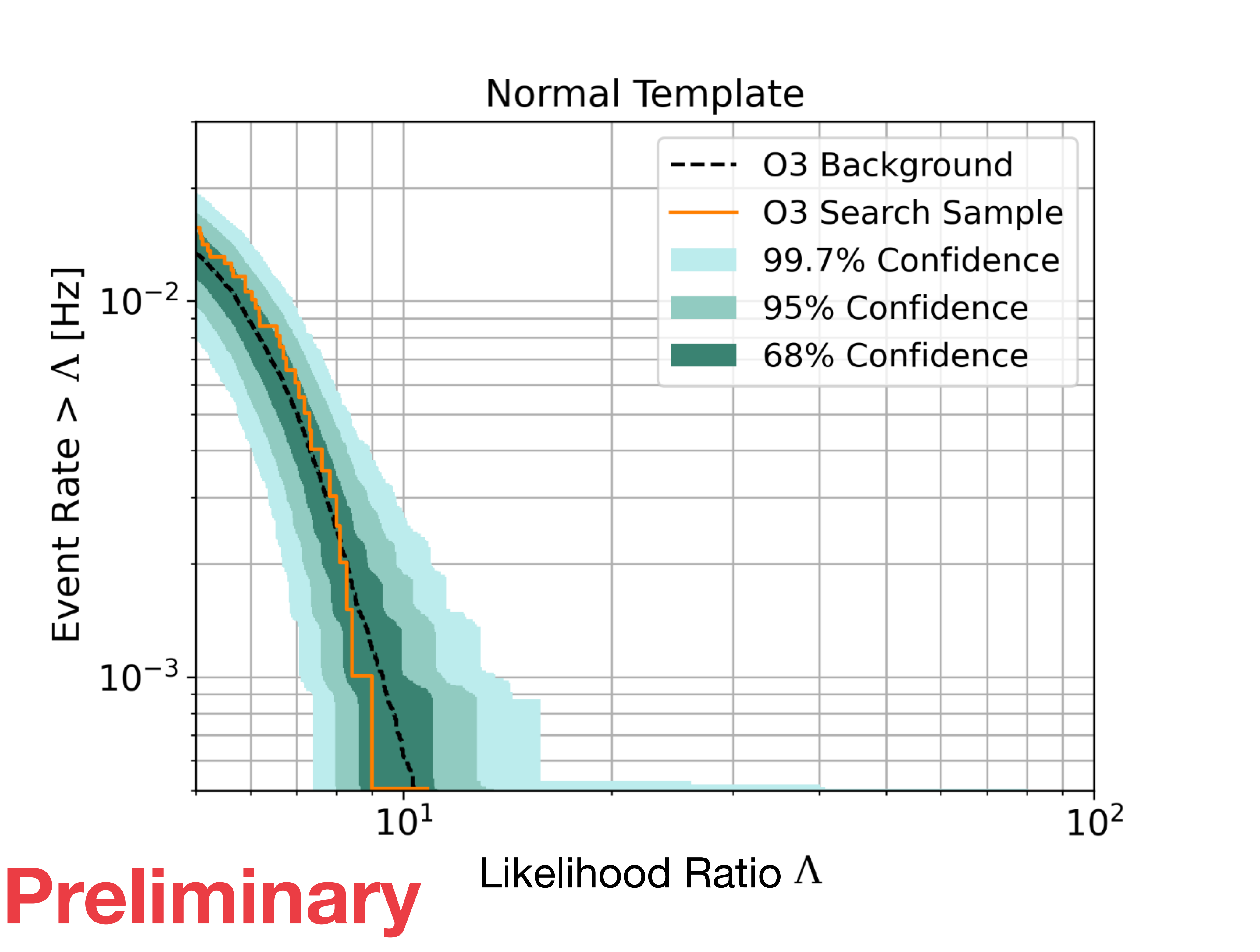
Fermi-GBM Searches

- **No on-board GRB triggers** within 10 minutes of GW events with $p_{astro} > 0.5$
- Most sensitive method, the **Targeted Search**, scanned continuous time tagged event (CTTE) data [-1 s, +30 s] around each GW event. Uses a likelihood ratio test identify GRB-like transients with 3 characteristic spectral templates (soft, normal, hard). **Found no significant GRB counterparts**.

Example Targeted Search for GRB 170817A

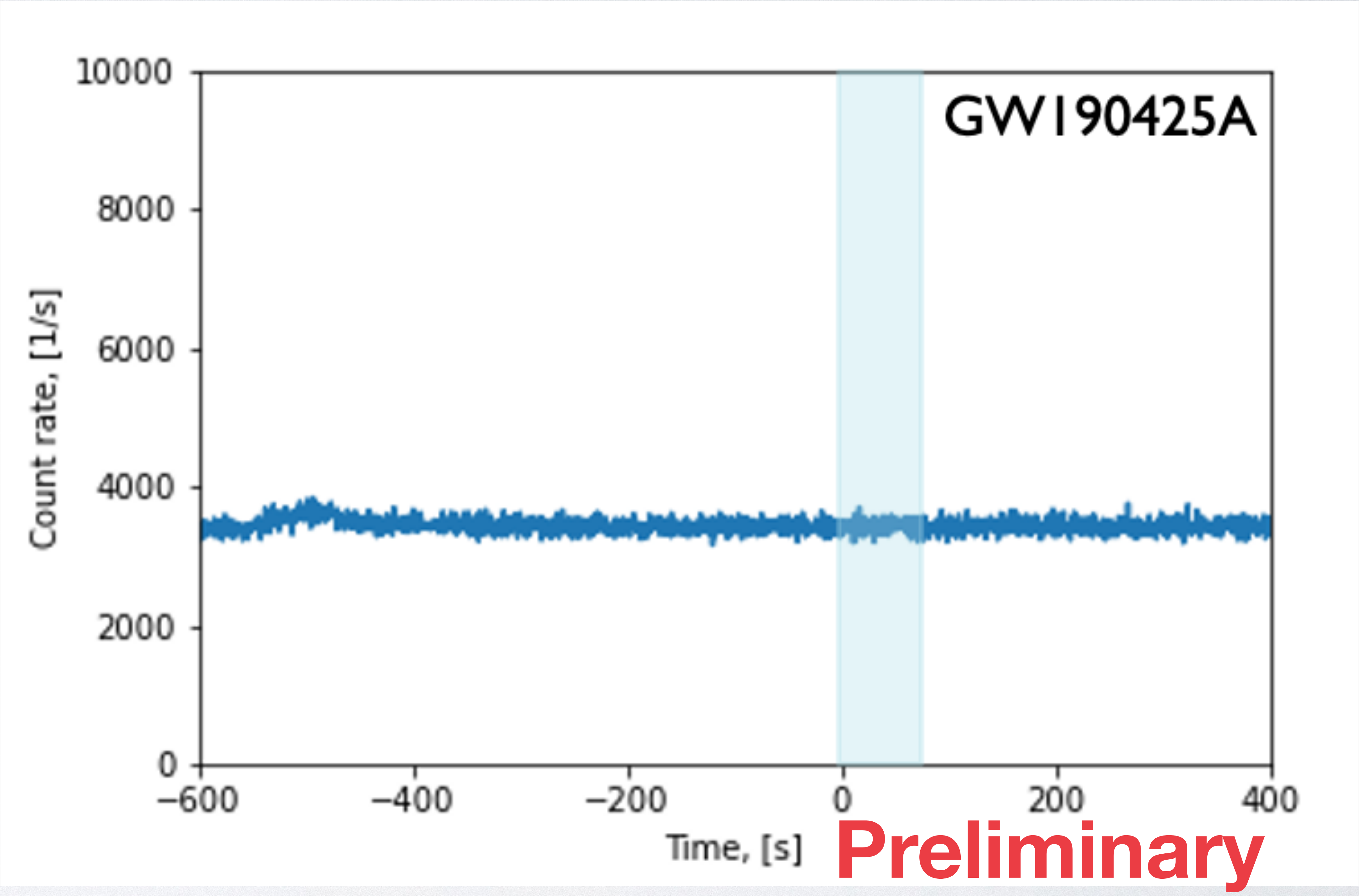


Kocevski et al. *ApJ.* (2018)



Swift-BAT Searches

- **No on-board GRB triggers** associated with GW events with $p_{astro} > 0.5$
- Also applied a rates based search to scan for 1-second long transients [-1 s, +30 s] around each GW event. **No significant counterparts found, defined as ≥5σ above background.**

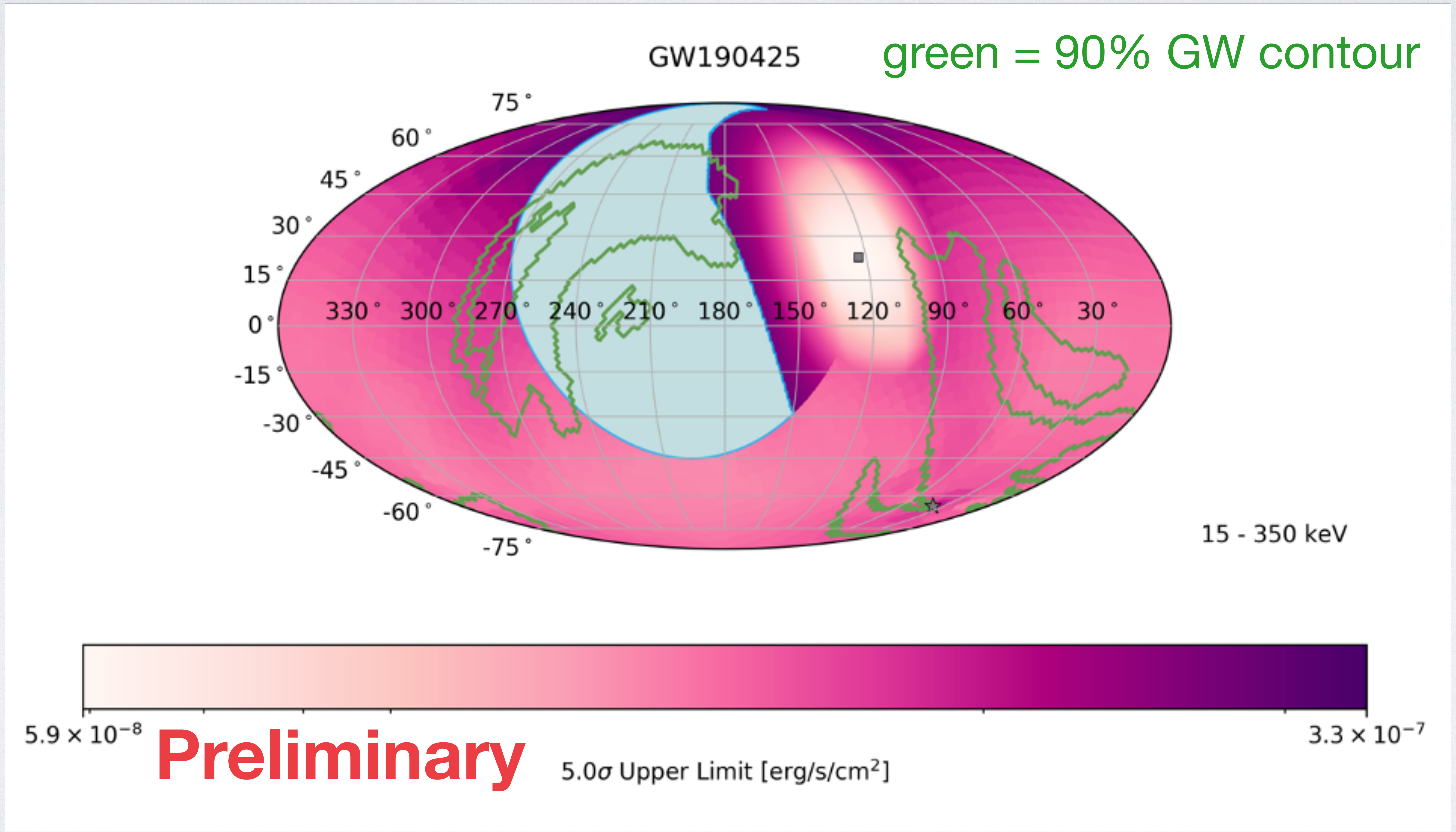


- **Note:** newer GUANO technique enables downlink of full Swift dataset near GW triggers. Implemented in the middle of O3, will be fully applied to next observing run.

Aaron Tohuvavohu *et al* 2020 *ApJ* **900** 35

Interpreting Non-detections

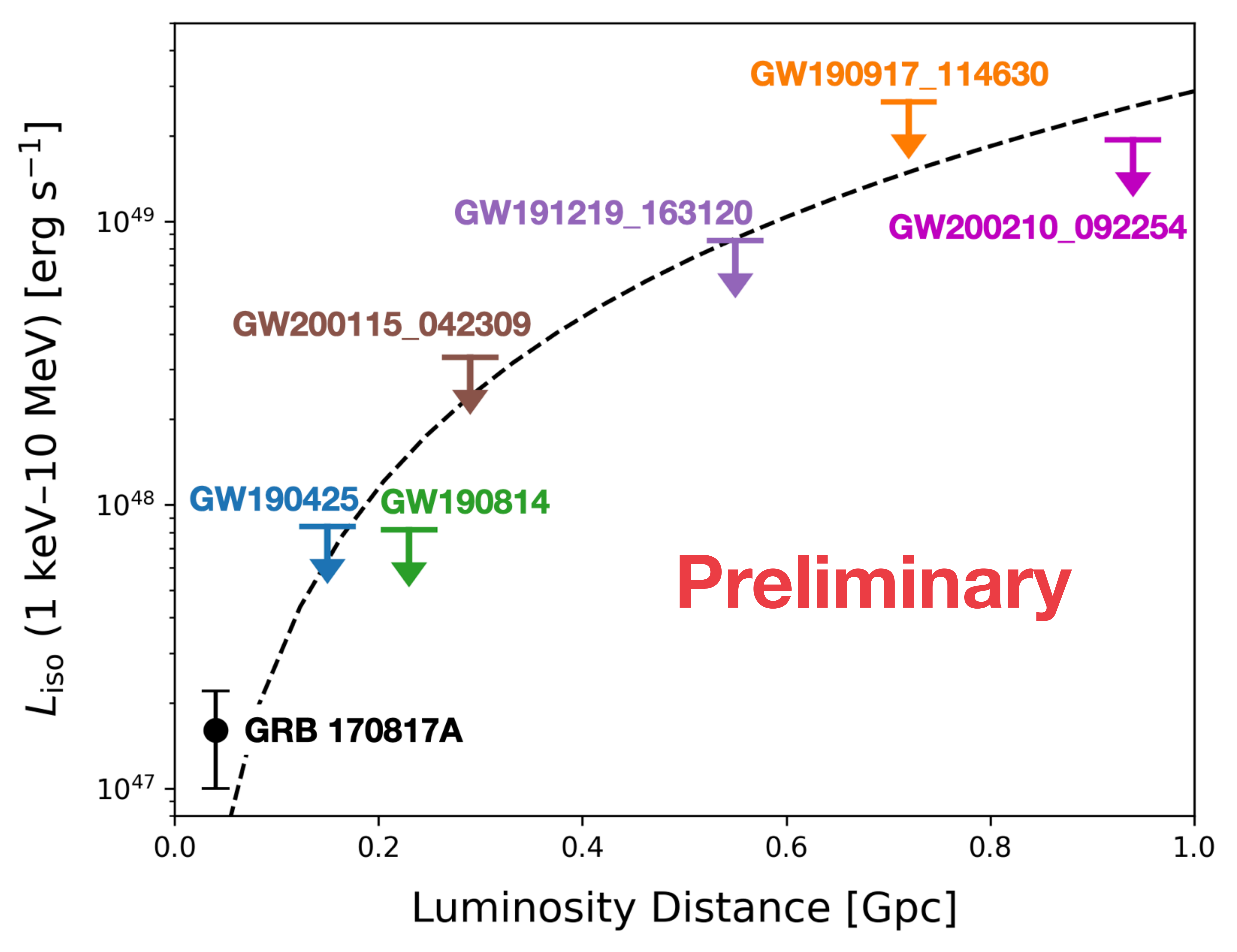
- Using the GBM Targeted Search and the BAT 1-s rates search we can set flux upper limits as a function of sky position



Upper limits assuming a Band spectrum (E_{peak} 230 keV, α = -1, β = -2.3)

Interpreting Non-detections

- We also calculate isotropic-equivalent luminosity upper limits (U.L.) using marginalized flux U.L. + luminosity distance
- **For the only BNS event GW190425** luminosity distance of 150 Mpc yields **L_{iso} ~ 8.4x10^{47} erg/s >> GRB 170817A which is not constraining**
- **Other reasons for the non-detection of GW190425:**
  - 60% sky coverage
  - viewing angle could too far off the jet axis



Upper limits assuming a Band spectrum (E_{peak} 230 keV, α = -1, β = -2.3)

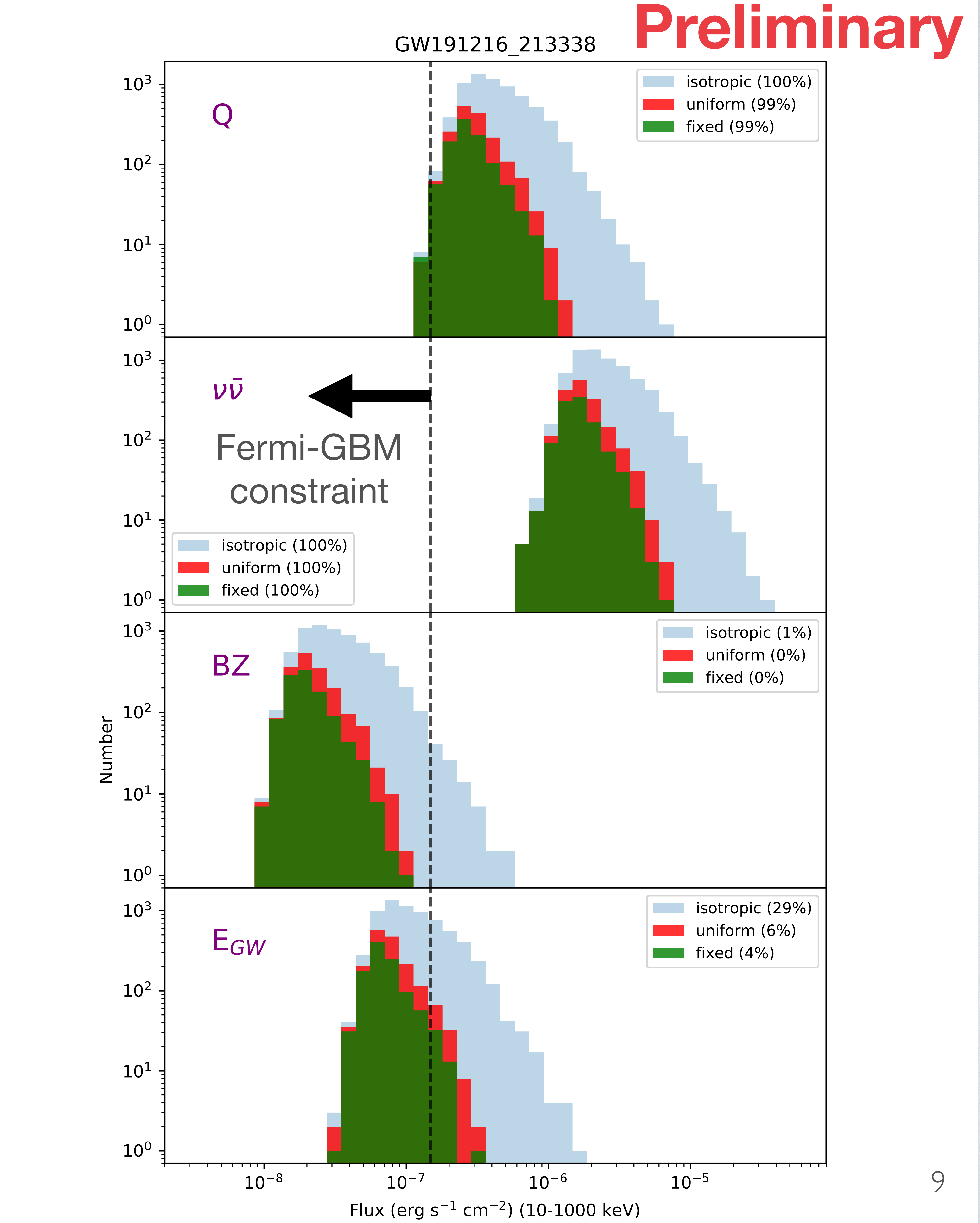
Interpreting Non-detections

- Sheer volume of BBH events provides a few nearby, very massive systems that would have yielded a strong EM signal under a neutrino anti-neutrino ($\nu\bar{\nu}$) annihilation driven wind scenario

GW191216_213338

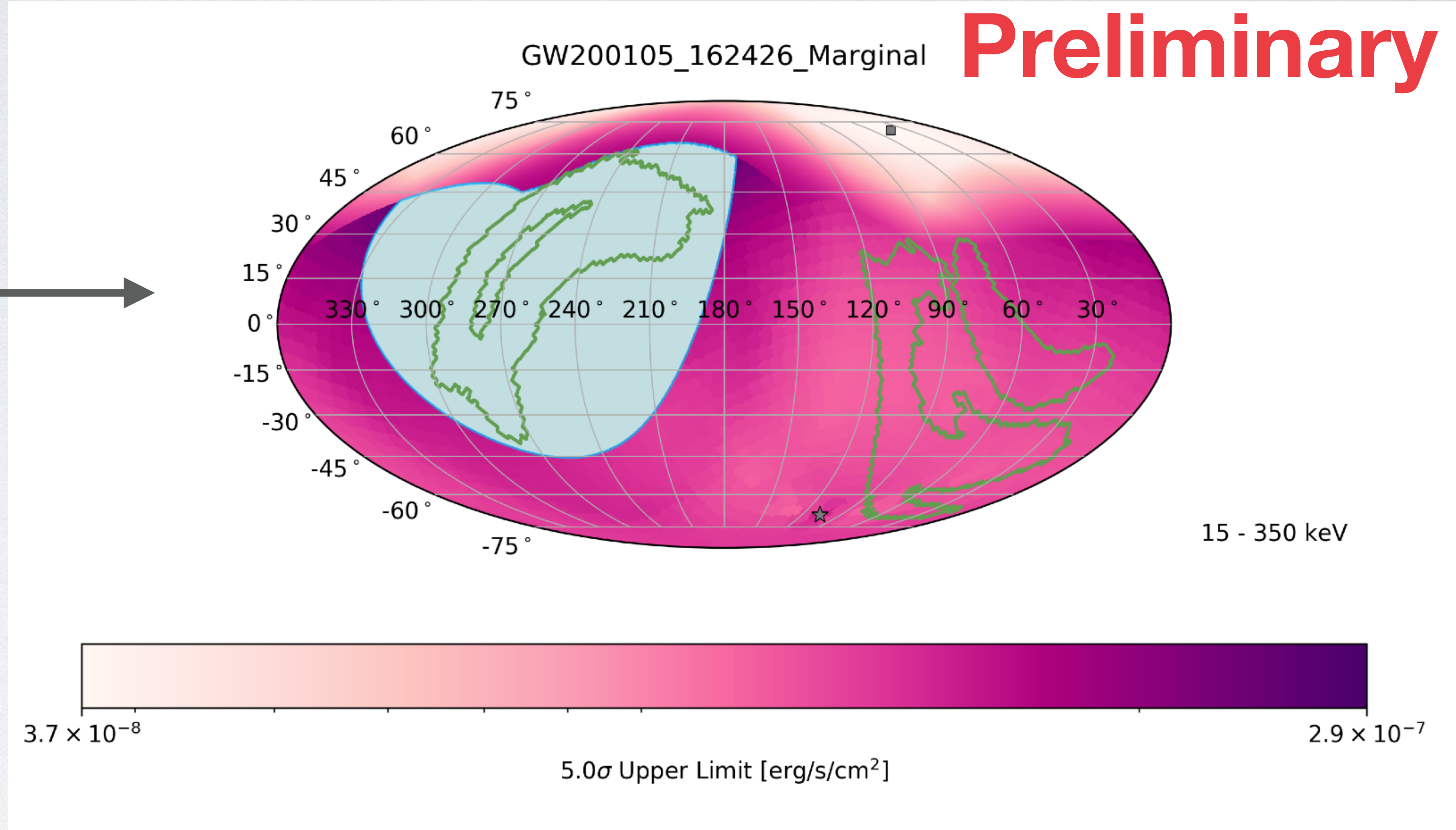
D_L 340 Mpc → closest BBH in O3
m1 12.1 Msun
m2 7.7 Msun

- **Details**: Simulate a population of EM emission scenarios, check which fraction are ruled out by gamma-ray flux upper limits. BBH parameters sampled from posterior distributions, GRB opening angles sampled from isotropic (90°), uniform 10-40°, fixed 20° cases

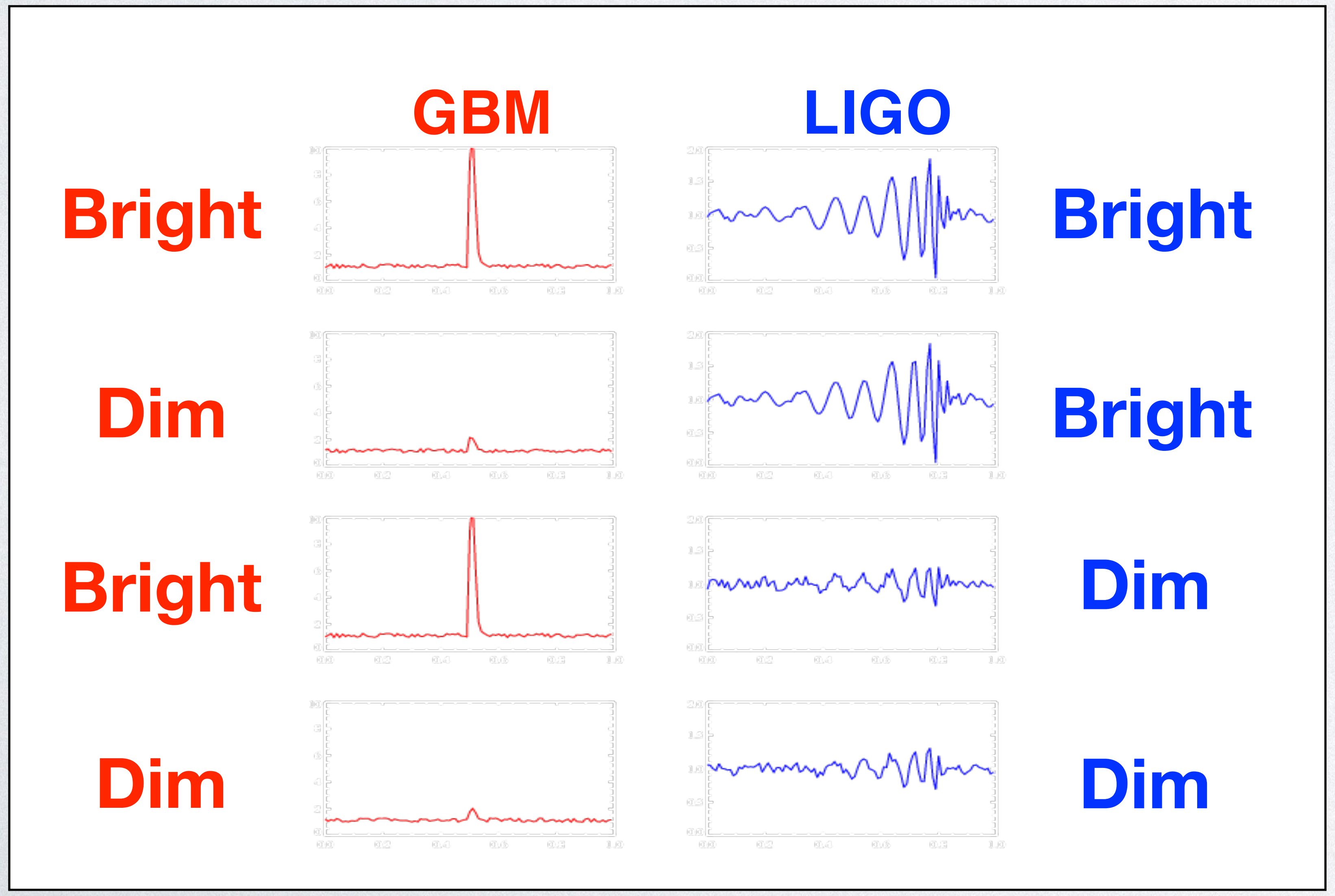


What about the marginal GW events?

- Set of marginal GW events (FAR < 2 per year, p_{astro} < 0.5) from O3 contain several low-mass systems which could be BNS or **NSBH**



- Applied the same Fermi-GBM and Swift-BAT searches to see if we could confirm any systems as astrophysical with a GRB counterpart. **No significant detections**.



- **Note:** Fermi-GBM, Swift-BAT, and many others are working on digging even deeper into the joint sub-threshold regime. See C. Stachie at al 2022 ApJ **930** 45, Aaron Tohuvavohu *et al* 2020 *ApJ* **900** 35, etc for more details

Summary

- LIGO, Fermi-GBM, and Swift-BAT are working together to enhance the number of joint GRB-GW detections, as best we can.
- No significant detection of a GRB counterpart to GW events with $p_{astro} > 0.5$ during O3
- **BNS/NSBH upper limits are not constraining**, for sure due to increased event distances compared to GW170817 but also partial coverage in some cases, potentially unfavorable viewing angles
- **BBH upper limits are constraining for some systems & models** ($\nu\bar{\nu}$)
- Rapidly approaching O4 will provide additional opportunities for joint detection of a BNS event, lots more BBH events to further constraint BBH models

Backup

Additional Details on the Targeted Search

- Likelihood implementation described in L. Blackburn et al 2015 ApJS 217 8 where $\tilde{d}_i$ are the background subtracted counts in each GBM detector, r_i are the detector responses, s is the source photon flux, σ_{ni} and σ_{di} are the standard deviations of background and $\tilde{d}_i$, respectively

$$\mathcal{L}(d,s) = \sum_i \left[\ln\frac{\sigma_{n_i}}{\sigma_{d_i}} + \frac{\tilde{d}_i^2}{2\sigma_{n_i}^2} - \frac{(\tilde{d}_i - r_i s)^2}{2\sigma_{d_i}^2} \right]$$

- Computed separately for each point on the sky using detector responses for 3 characteristic spectra describe most GRBs seen by GBM

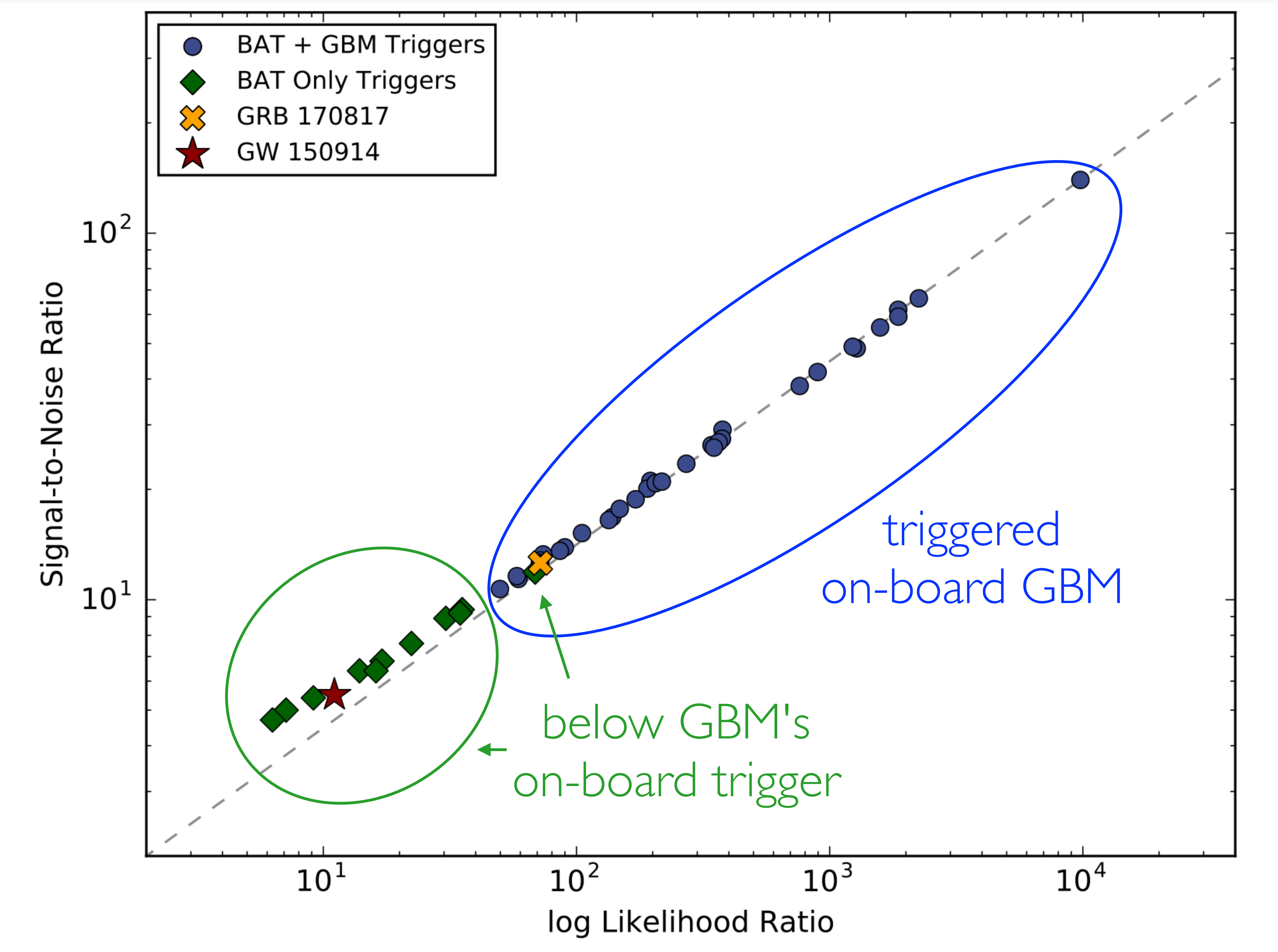
Table 3. Spectral templates used by the *Fermi*-GBM Targeted Search.

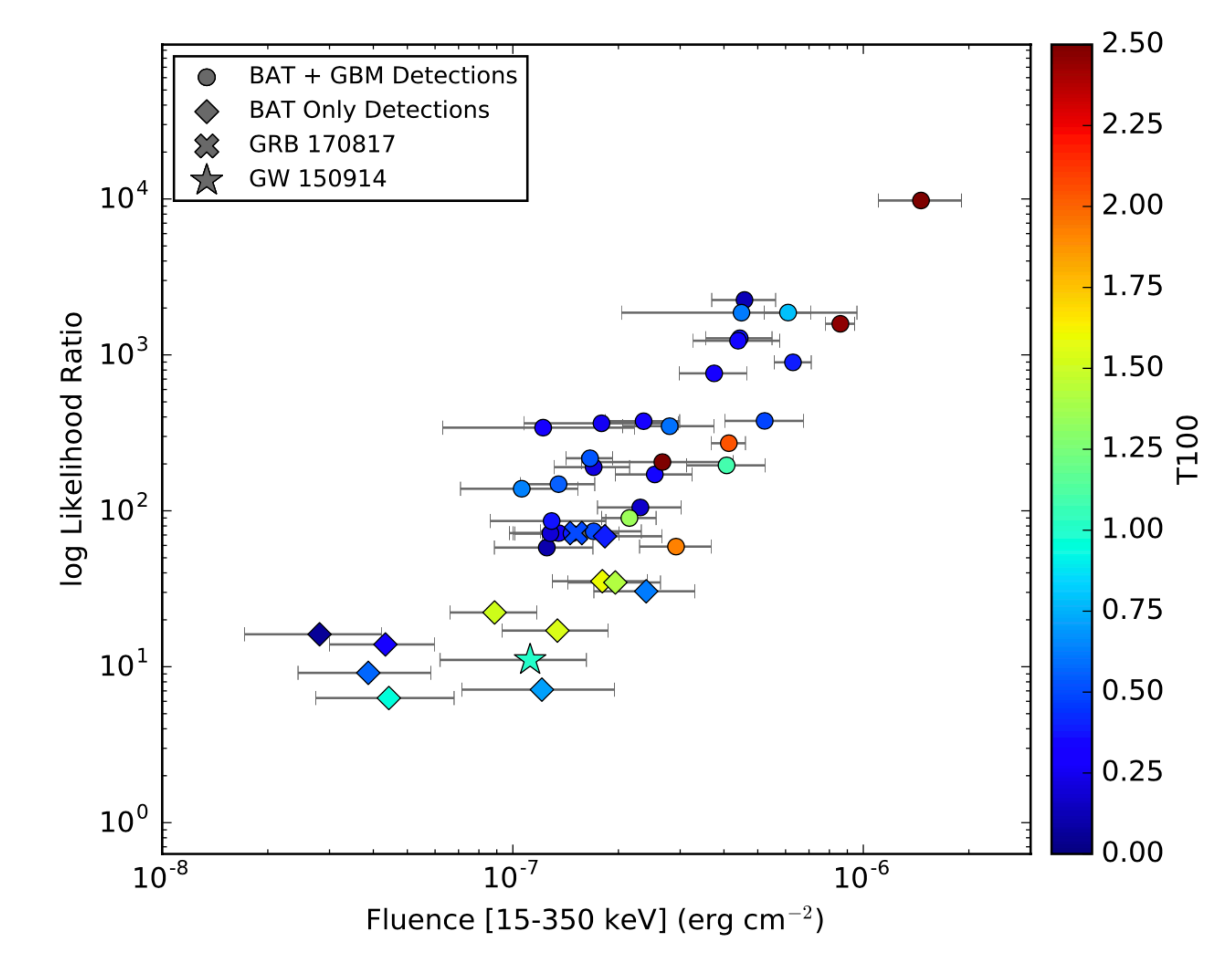
Template	Type	Parameters
hard	Cut-off Power-law (Goldstein et al. 2016)	$E_{peak} = 1500$ keV, $\alpha = -1.5$
normal	Band (Band et al. 1993)	$E_{peak} = 230$ keV, $\alpha = -1.0$, $\beta = -2.3$
soft	Band (Band et al. 1993)	$E_{peak} = 70$ keV, $\alpha = -1.9$, $\beta = -3.7$

- Logarithm of the the likelihood is marginalized over the sky, spectral templates, and source flux

Additional Details on the Targeted Search

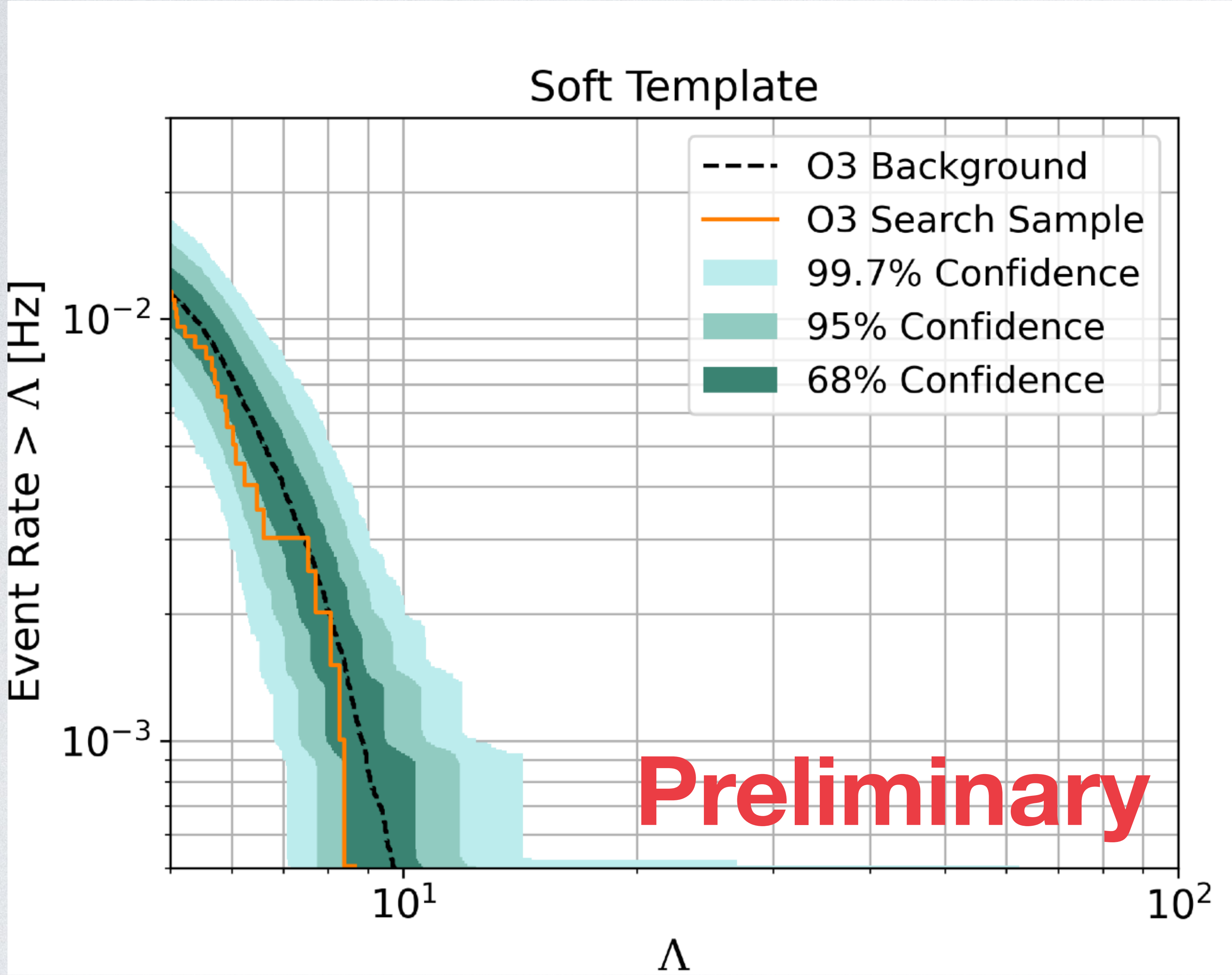
- Proven to recover short gamma-ray bursts that are below the on-board trigger threshold in GBM

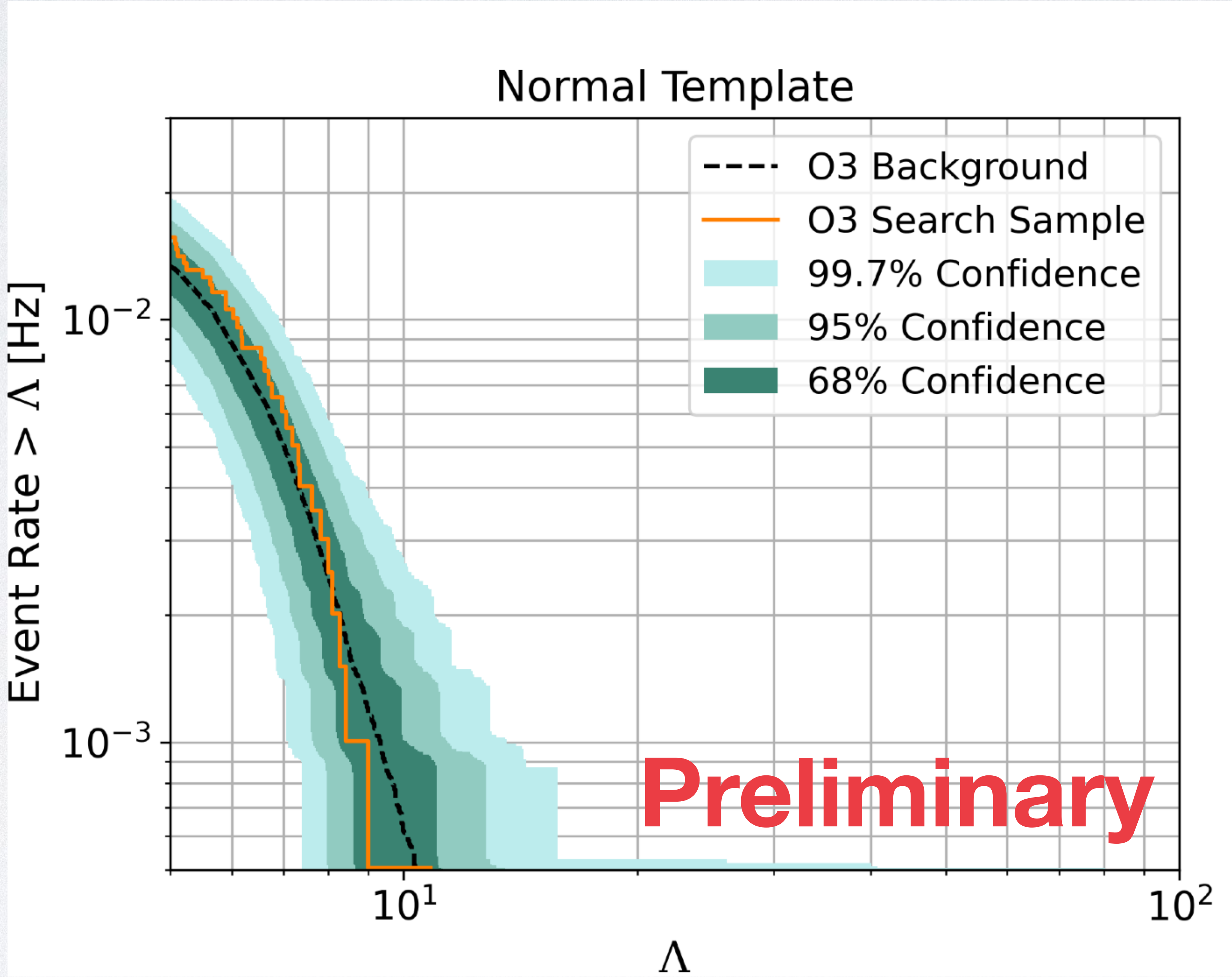


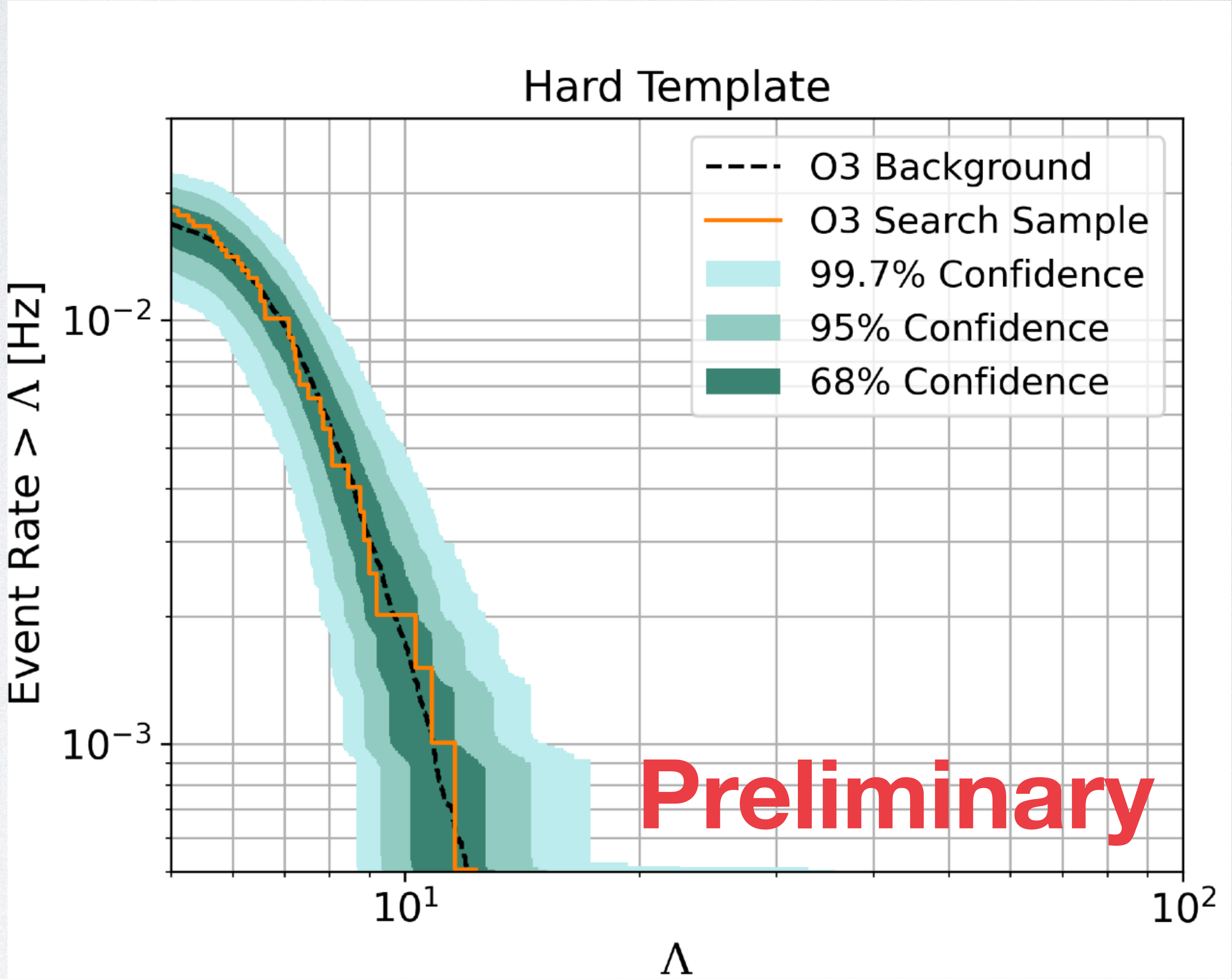


Kocevski et al. *ApJ.* (2018)

Targeted Search Results from All Spectral Templates

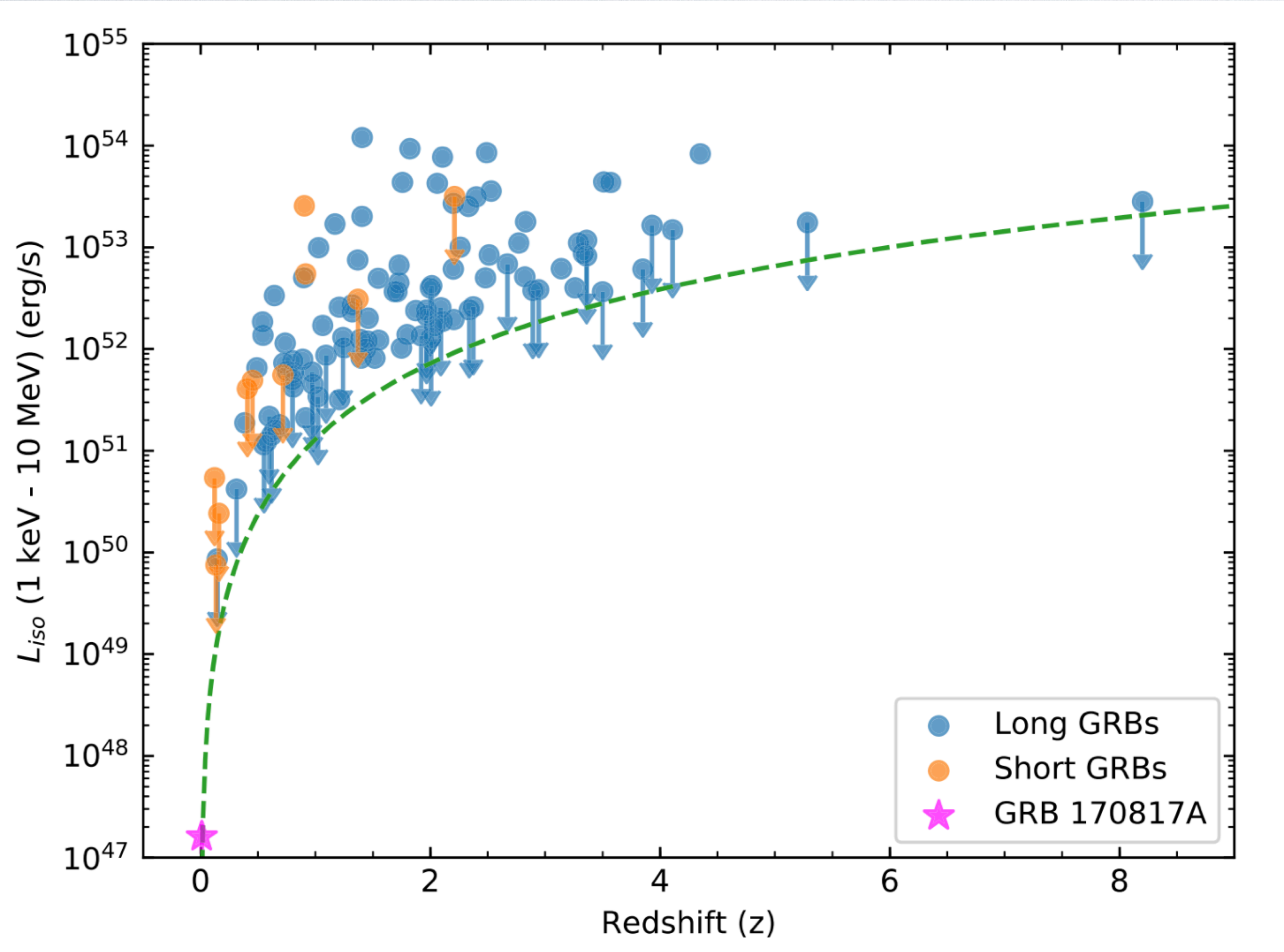




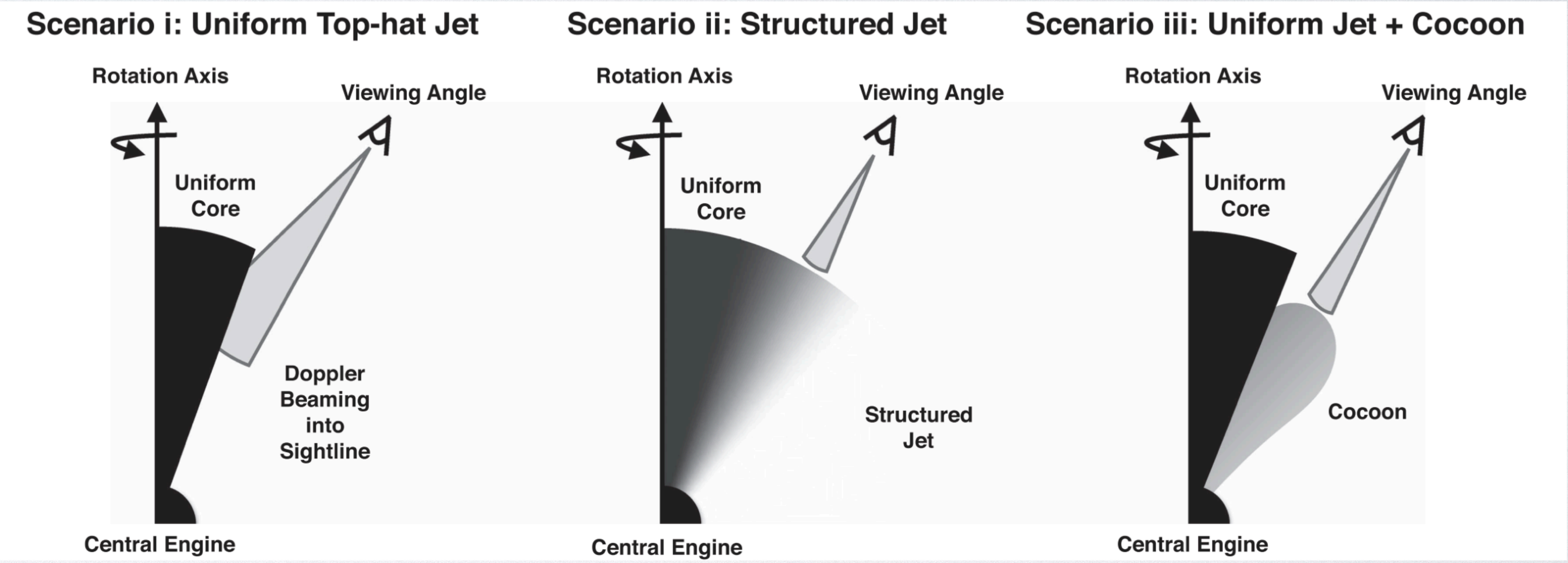


GRB 170817A / GW170817

- Gamma-ray emission from GRB 170817A is notable because it is nearby (40 Mpc), intrinsically dim
- Points to an off-axis viewing angle, many questions remain about the off-axis jet structure in this GRB



B. P. Abbott *et al* 2017 *ApJL* **848** L13

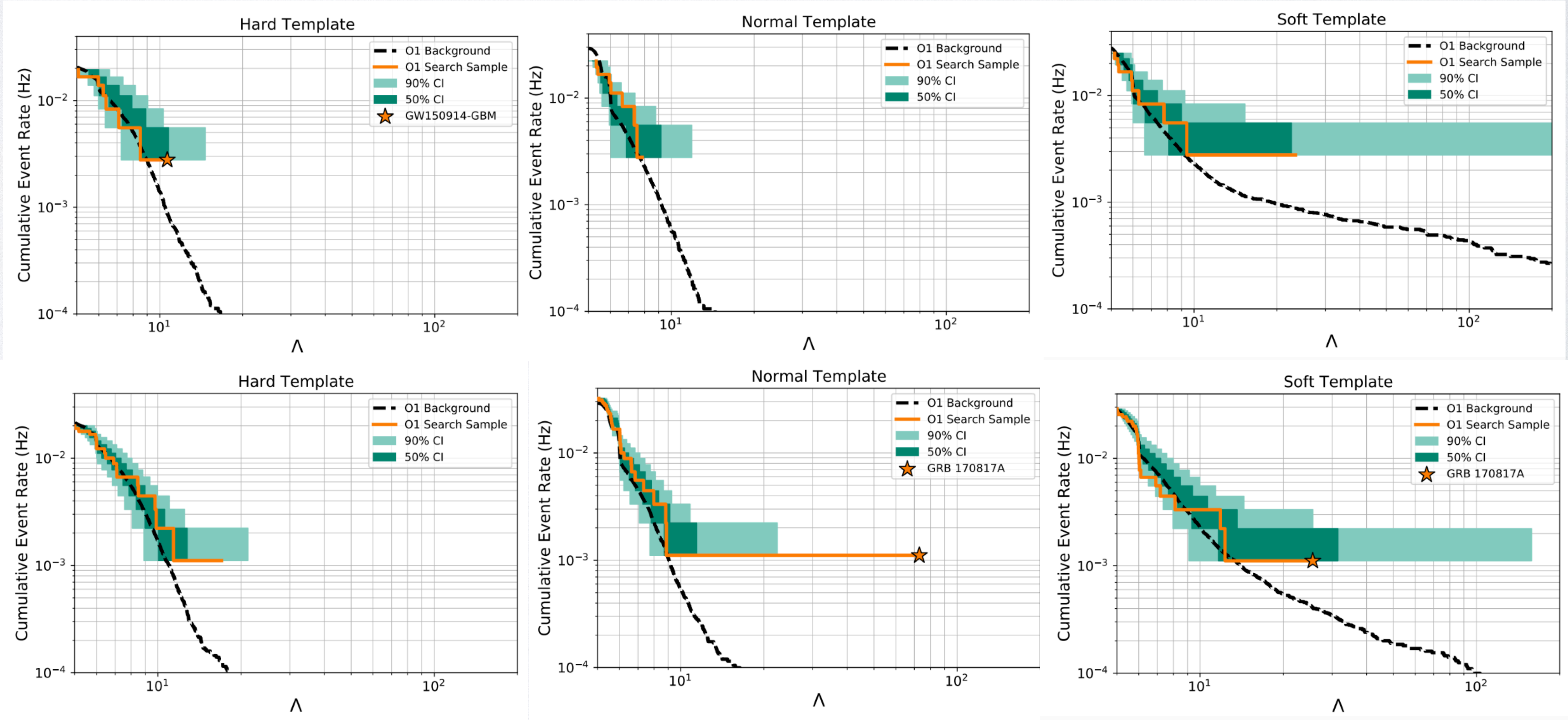


- We hope to address these questions through additional detections of GRB counterparts to GW events in Fermi-GBM

Searching O1/O2 Catalog Events

LIGO/Virgo GW Event	UTC Date	UTC Time	p_{astro}	GBM Coverage
GW150914	2015-09-14	09:50:45.4	1	66.7%
151008	2015-10-08	14:09:17.5	0.27	100%
151012.2	2015-10-12	06:30:45.2	0.023	58.4%
GW151012	2015-10-12	09:54:43.4	1	66.1%
151116	2015-11-16	22:41:48.7	$\ll$0.5	72.6%
GW151226	2015-12-26	03:38:53.6	1	78.8%
161202	2016-12-02	03:53:44.9	0.034	-
161217	2016-12-17	07:16:24.4	0.018	-
GW170104	2017-01-04	10:11:58.6	1	90.3%
170208	2017-02-08	10:39:25.8	0.02	97.8%
170219	2017-02-19	14:04:09.0	0.02	5.1%
170405	2017-04-05	11:04:52.7	0.004	-
170412	2017-04-12	15:56:39.0	0.06	67.2%
170423	2017-04-23	12:10:45.0	0.086	45.2%
GW170608	2017-06-08	02:01:16.5	1	73.0%
170616	2017-06-16	19:47:20.8	$\ll$0.5	66.2%
170630	2017-06-30	16:17:07.8	0.02	8.2%
170705	2017-07-05	08:45:16.3	0.012	26.3%
170720	2017-07-20	22:44:31.8	0.0097	48.2%
GW170729	2017-07-29	18:56:29.3	0.98	88.9%
GW170809	2017-08-09	08:28:21.8	1	73.9%
GW170814	2017-08-14	10:30:43.5	1	73.6%
GW170817	2017-08-17	12:41:04.4	1	100%
GW170818	2017-08-18	02:25:09.1	1	100%
GW170823	2017-08-23	13:13:58.5	1	-

- We applied the targeted search to all GW events reported in the LIGO/Virgo catalog of GW events from the first (O1) and second (O2) observing runs (**Abbot et al. 2019 PhysRevX, 9, 031040**)
- Below are the false alarm rate distributions for the likelihood ratios of EM emission candidates recovered during the search across the three characteristic spectral templates.



R. Hamburg *et al* 2020 *ApJ* **893** 100

Joint Sub-Threshold Candidate GBM-190816 reported during O3

- One interesting candidate found during O3 involved a **weak** GW candidate signal and a **weak** EM candidate in GBM

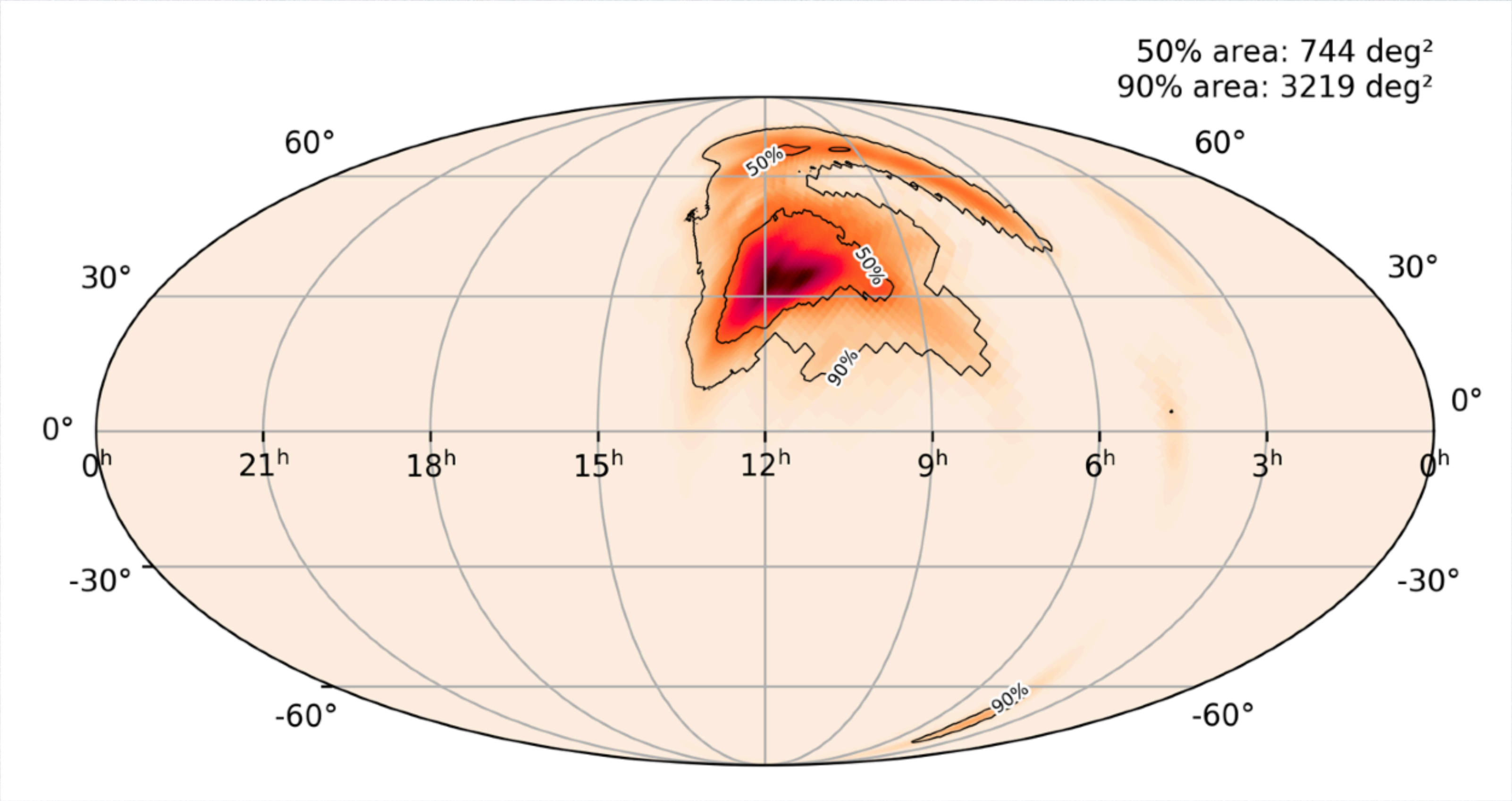
- L1 & V1 observed the compact binary merger candidate at 21:22:13 UTC on 2019-08-16
  - Did not exceed public FAR limit
  - Lighter compact object with < 3 M_{sun}
  - Sent to GBM through our partnership with LVC

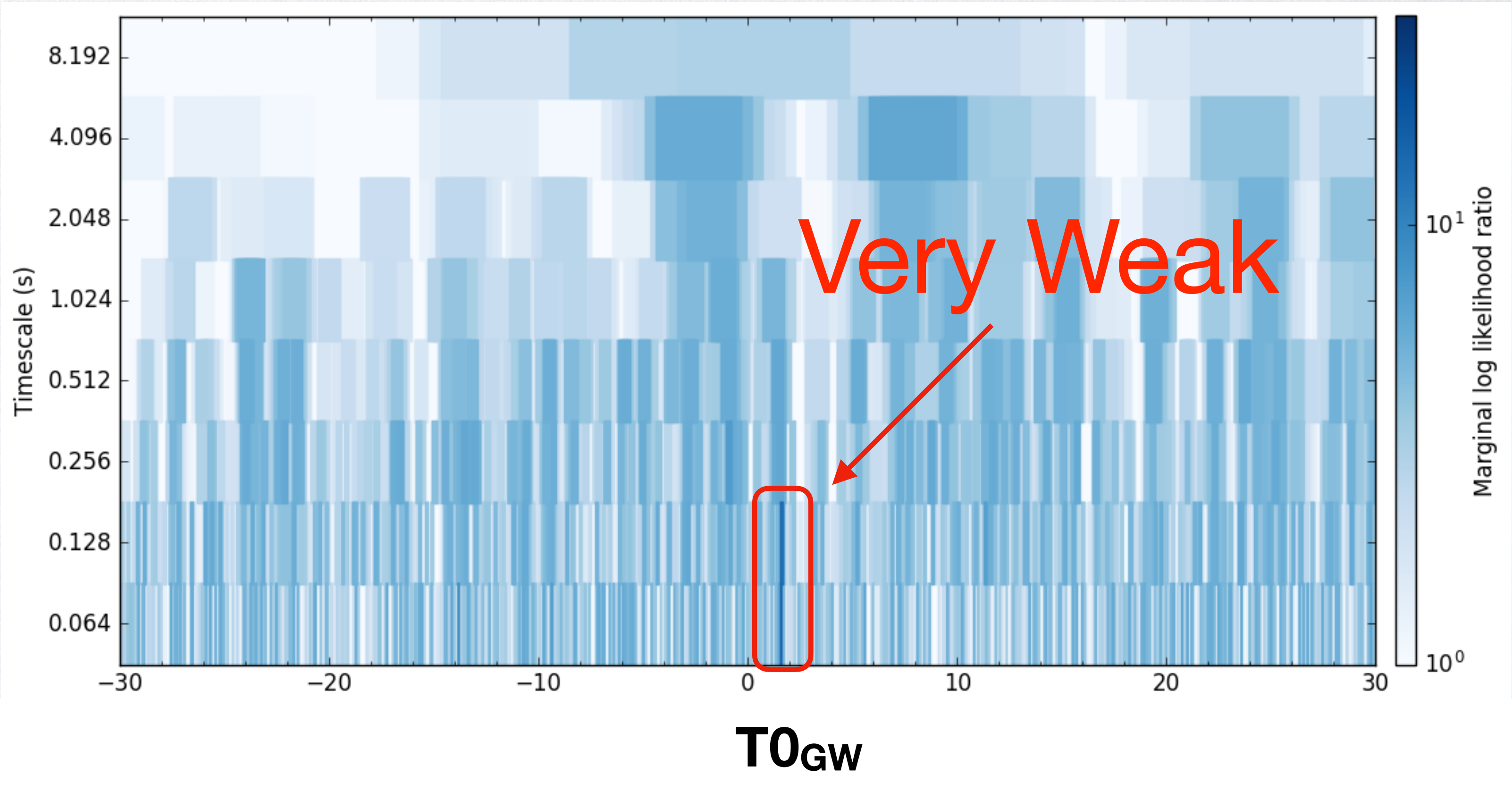
- GBM targeted search identified a very weak EM candidate at $T0_{GW}$ + 1.5 s, ~0.1 s long

- Joint false alarm rate of ~1-2 per month

- Resulted in follow-up observations but no kilonova or afterglow candidates so **neither the GW candidate nor the EM candidate could be confirmed.**

Fermi GBM-190816





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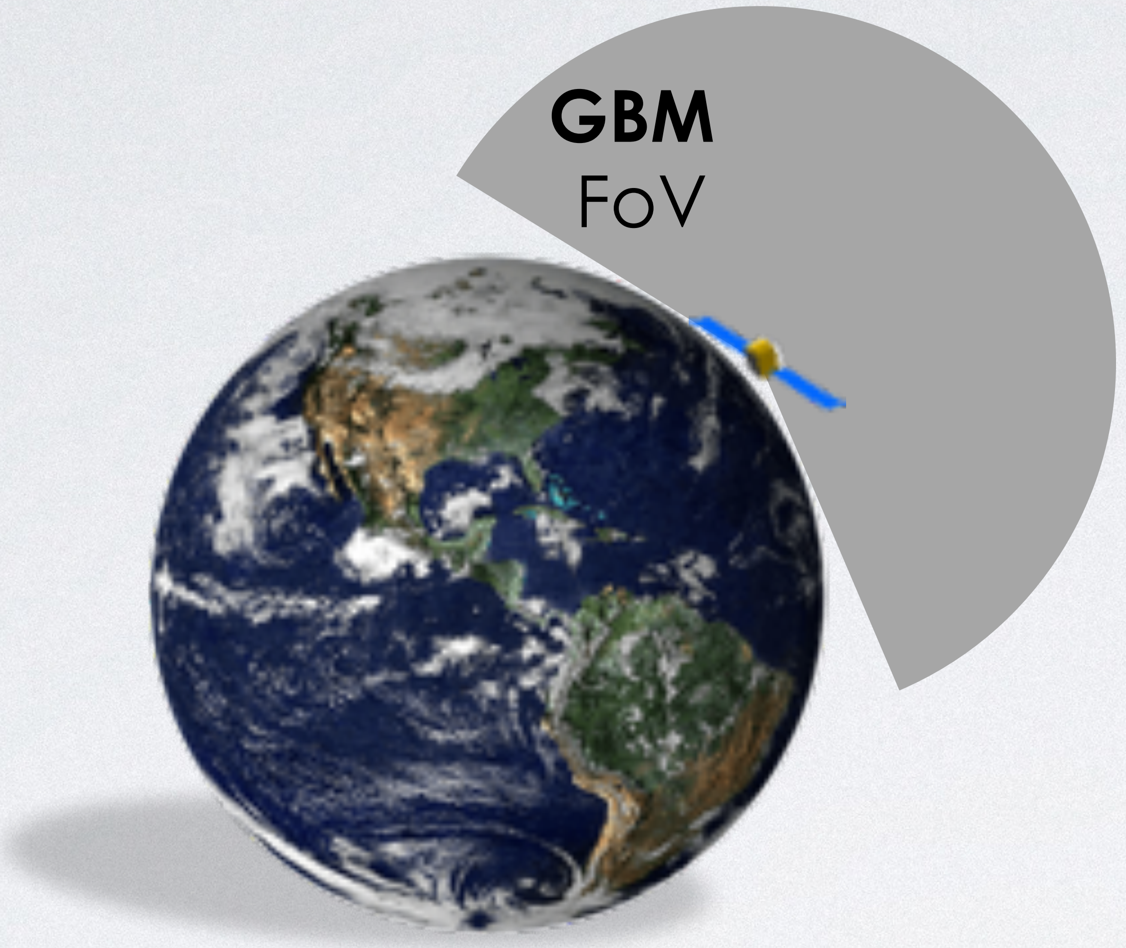

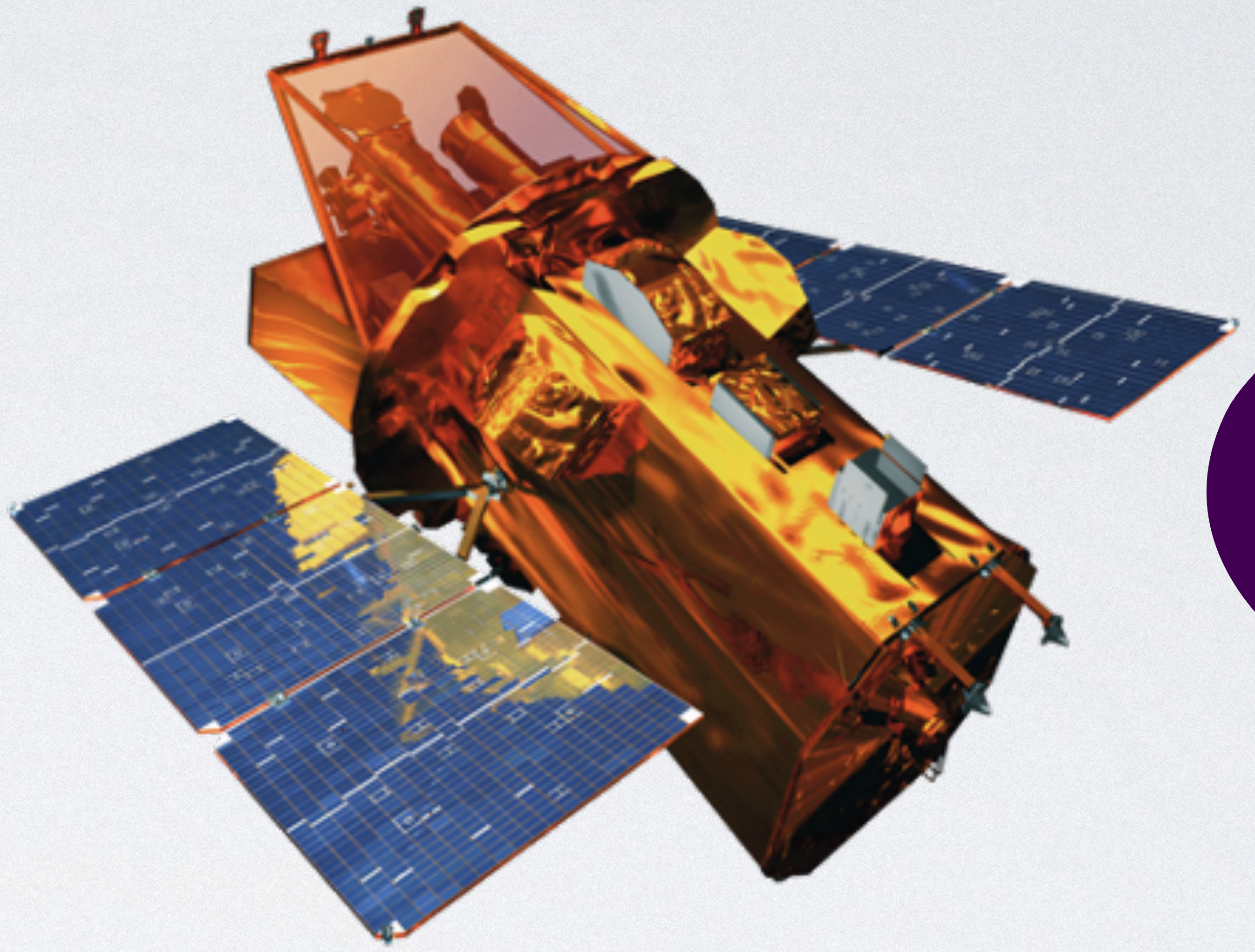

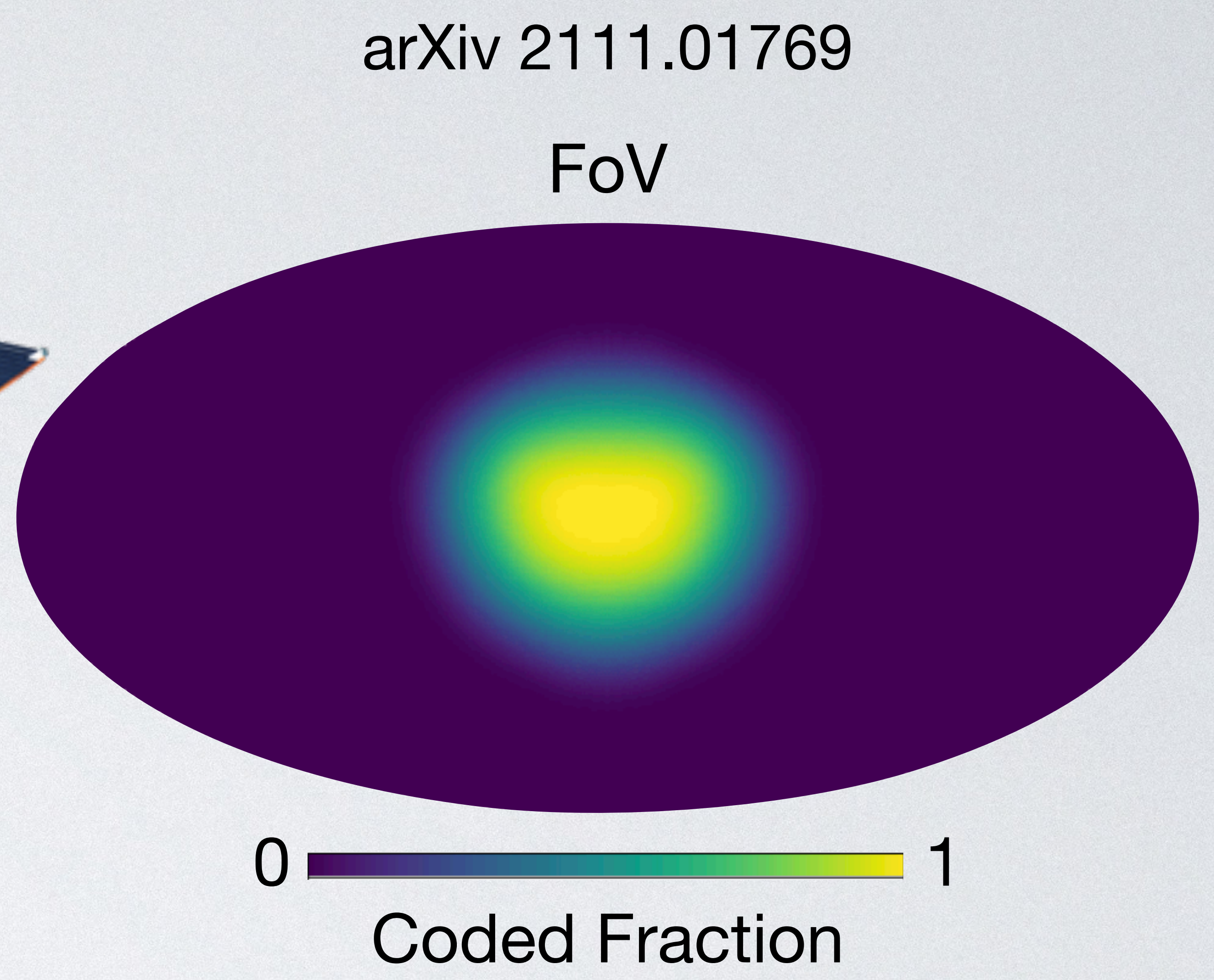

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